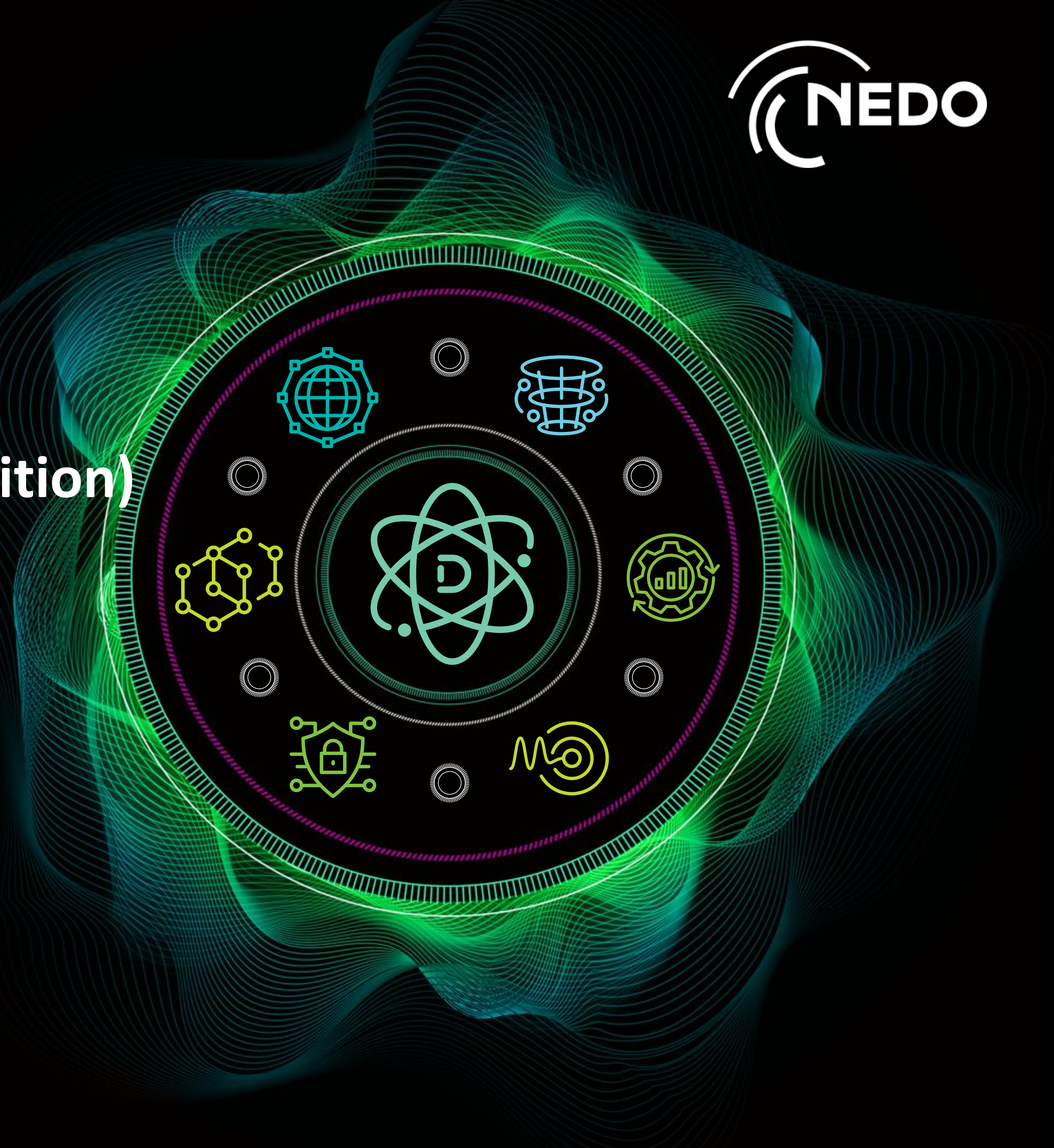
Quantum Computer
Compendium of Use Cases(Second Edition)



New Energy and Industrial Technology Development Organization (NEDO)

About this Compendium of Use Cases

- The United Nations General Assembly has designated 2025 as the International Year of Quantum Science and Technology to mark the centenary of the birth of quantum physics. Among technologies that leverage the properties of quantum mechanics, quantum computers have attracted great expectations and continue to advance. In April 2022, the Government of Japan formulated the “Quantum Future Society Vision,” and since then has continued to issue policy documents and pursue initiatives aimed at creating and developing the quantum industry.

- Against this backdrop, the New Energy and Industrial Technology Development Organization (NEDO) has, since fiscal year 2023, promoted the development of quantum computer use cases under the “Cyber-Physical Development Project for Quantum–Classical Hybrid Technology,” while collecting and analyzing examples of quantum computer applications, culminating in the publication of the “Quantum Computer Use Case Compendium” in February 2025.

- This document is a revision prepared roughly one year after the first edition, adding the latest cases, refreshing the structure, and organizing more detailed information in an accessible manner. It surveys examples across a wide range of fields—including manufacturing, drug discovery and healthcare, finance, transportation, and energy—and explains, from a business-use perspective, how quantum computers are being applied to specific challenges. It is intended to provide organizations that are interested in quantum computing but have yet to begin concrete evaluations with pointers for taking the first step toward considering practical use.

Structure of this Use Case Collection

CHAPTER 1 Use case trends

- Based on all the examples listed, we describe the trends in use cases using quantum computers in each field.

Chapter 2 List of use cases

- Six industrial areas (Discrete Manufacturing, manufacturing processes, drug discovery&medical care, finance, transportation, energy) x four applications (Advanced combinatorial optimization, advanced AI, advanced simulation, advanced cryptanalysis) are introduced.

Appendix (1) List of quantum computer vendors

- List and organize quantum service vendors that you can refer to as you work on developing and implementing use cases.

Appendix (2) Related Academic Papers

- List and organize scholarly articles that you can refer to as you work on developing and implementing use cases.

Considerations for this Use Case Collection

- The examples and companies included in this collection of use cases are only examples and do not include examples and companies in Japan and overseas.
- Although some examples cover multiple areas, they are classified according to the area to which the main content of each example belongs.
- We are based on published materials, but we do not guarantee or promise the accuracy or completeness of the information.
- The source URLs listed in this document were accessed and verified as of March 2026. Subsequent updates, relocations, or deletions may result in broken links.

Chapter 1 Use case trends

Discrete Manufacturing Use case trends

In the area of Discrete Manufacturing, we will work to optimize individual operations in the current supply chain, but in the future we will work to optimize the entire supply chain.

Primary use

Major use cases are procurement, production, product design, process design and sales operations, and optimization.

- Complex production planning automation, collaborative shift optimization between humans and robots, improved utilization of automated guided vehicles, etc.

Business areas that still have room for manpower are particularly promising

- At present, it is difficult to show superiority over classical computers, so there is a great need to use them for setup changes, shift planning, etc., where conventional DX adoption has not progressed.

Business Impact and Maturity

Currently responsible for cost reduction in individual supply chain operations

- More than a cost benefit for companies with expert succession issues

Some use cases go to practical use

- There are several cases where quantum-inspired solutions are already in production
- Currently, only some advanced companies that have the capacity to invest in it are using it.

Adoption challenges

Clarifying the superiority of quantum computers

- It is difficult to demonstrate the superiority of quantum computers over conventional methods in warehouse management, logistics management, etc., where classical computers are being introduced.

On-site coordination, data preparation and standardization

- Even if the management recommends it, the practical application will not be realized unless the field agrees.
- Business know-how is in the mind of the expert, and in many cases it is not clearly written.
- Standardization of data across departments and systems is necessary to optimize the entire supply chain

Future Prospects

In the future, it is expected to be used for optimization of the entire supply chain.

- Currently, optimization of individual operations such as process design and in-plant logistics is the main focus, but in the future, optimization of the entire supply chain such as production planning, inventory management and logistics planning is expected.

Combination with classical computers and improvement of environment such as organizational design

- It is important to use the needs of the site as a starting point, and to separate and combine the existing methods.
- In addition to KPI design and organizational design across the supply chain, data preparation as a prerequisite for DX is important.

Discrete Manufacturing use case organization

In the area of Discrete Manufacturing, we were able to confirm use cases centering on optimization of layout in process design and optimization of transportation in shipping and sales.

Green text: Use cases added in the second edition.
Underlined: Practical-application use cases.
This field is also explained in "Manufacturing and Process," etc.

Process

R & D and product design

process design

order and procurement → Production → Shipping and sales

Use Case

order and procurement

- ✓ Air Cargo Placement Optimization

Production

Research and development product design

- ✓ Optimization of aerodynamic characteristics in aircraft design
- ✓ Improving Jet Engine Performance
- ✓ Optimization of Decoupling Capacitors in Four-Layer Printed Circuit Boards
- ✓ Vehicle design optimization using black box optimization

process design

- ✓ Factory Equipment Layout Optimization Using Quantum Computers
- ✓ Optimizing the Storage and Arrangement of Vehicle Supply Parts at the Parts Center
- ✓ Reducing travel distance for parts aggregation in warehouses
- ✓ Optimization of Picking Routes and Shelf Arrangements in Factories and Warehouse
- ✓ **Improving efficiency in automotive computer design**

Production

- ✓ Complex Production Planning Automation
- ✓ Optimizing Collaborative Shift between Humans and Robots
- ✓ **Improving efficiency of semiconductor manufacturing processes**

Shipping and sales

- ✓ Improve the availability rate of automated guided vehicle (AGV) at factories
- ✓ Efficiency of preparation of loading plans for car carriers
- ✓ Increase efficiency of large-scale logistics

Use Case Trends **in Manufacturing, Process, and Drug Discovery**

In the fields of manufacturing, process, and drug discovery, there are use cases that contribute to shortening the R & D period and developing new materials and drugs. Advanced companies are working on R & D with an eye to developing computational algorithms for material development

Primary use

The main use cases are shortening the research and development period by efficiently searching for material candidates and drug discovery candidates, and accelerating the development of new materials and drug discovery.

- Prediction of physical properties of materials, analytical simulation of various chemical reactions, high-precision energy calculation for large-scale molecules and solids, search for candidate compounds for medium-molecule drugs, etc.
- In recent years, we have confirmed a hybrid R & D approach that uses AI to narrow down promising candidates and then performs quantum chemical calculations in order to respond to the search for a large number of material and molecular candidates.

Business Impact and Maturity

Technology maturity is low, but some advanced companies are starting to work on it

- Since the use of quantum gate technology is essential, it is far from practical. However, if quantum computers become widely used, the necessary machine resources may not be secured.
- Since different industries including IT companies/OEMs may enter the market, there is a possibility that they will be eliminated if they do not respond early.
- Therefore, it is possible to develop calculation algorithms for material development at an early stage and spread them as a de facto standard.

Adoption challenges

Development of gate technology and search for killer applications

- In addition to the low maturity of quantum gate technology, including algorithms and hardware, no specific killer application has been found that clearly demonstrates superiority and business benefits over conventional methods.

Future Prospects

Early understanding of users

- The main user in this area is the R & D department, which is already engaged in quantum scientific computing. This leads to understanding and practice of the benefits of introducing quantum computers.

Technical cooperation with overseas universities and research institutes

- In the future, collaboration with the world's most advanced researchers (such as the University of Toronto and NVIDIA in Canada) will lead to the strengthening of technological and human resources in Japan.

Manufacturing and Process Use Case Review

In the area of Process Manufacturing, we were able to confirm use cases mainly for material search in R & D.

Green text: Use cases added in the second edition.
Underlined: Practical-application use cases.

Process	research and development		
	material search		verification experiment / Evaluation
Use Case	✓ Molecular Simulation for Application to Automotive Material Design ✓ Modeling of Oxygen Reduction Reaction in Automotive Fuel Cell Development ✓ Prediction of material properties and simulation of various chemical reactions ✓ High-precision energy calculation for large-scale molecules and solids	✓ Material property prediction using existing material data × machine learning ✓ Improving the Design of Composite Materials for Aircraft	–

✓ Accelerated platform for material design and reaction analysis

Use Case Analysis **for Drug Discovery**

In the area of Drug Discovery and Healthcare, we were able to confirm use cases mainly for lead search and optimization in R & D.

Green text: Use cases added in the second edition.
Underlined: Practical-application use cases.

Process	**research and development**		
	drug target selection	lead search and optimization	clinical trial
Use Case	✓ Prediction of Allosteric Regulation of Proteins Expansion of drug discovery target	✓ Search for mid-molecule drug candidates ✓ Molecular simulations of the electronic structure of drug-metabolizing enzymes ✓ Lead compound against Alzheimer's disease-causing enzyme BASE1	–
	✓ **Genome analysis technology using quantum AI** ✓ Proof of Concept of Quantum AI Drug Discovery Process ✓ Development of anticancer drug candidates using quantum AI (spanning drug target selection and lead search and optimization)		

Financial Use Case Trends

In the financial sector, portfolio optimization and Monte Carlo simulation are the current killer applications, and we are also working on 3 mega companies with an eye toward future regulations.

Primary use

Key use cases include portfolio optimization, Monte Carlo simulation, and creditworthiness scoring

- Optimization of liquid asset portfolios, Monte Carlo simulation for derivative pricing, creditworthiness scoring of SMEs, etc.
- In particular, non-life insurance portfolio optimization and Monte Carlo simulation are killer applications

Applications to marketing and customer analysis are being considered.

- With the expansion of digital services by financial institutions, we also confirmed efforts to apply feature selection and optimization from user attributes to marketing analysis.

Business Impact and Maturity

Early Efforts by Advanced Companies in Advance of Regulatory Compliance

- Some advanced Japanese companies, including 3 Mega, are implementing quantum computers in Monte Carlo simulations from an early stage, anticipating the possibility that they will not be able to continue their business in the future due to compliance with regulations and guidelines or maintaining a competitive advantage (horror story).

Some use cases go to practical use

- There is a use case where CMOS annealing has started to be used in the non-life insurance underwriting business.

Adoption challenges

Maturity of quantum computing technologies related to FTQC

- At present, there are no cases where NISQ has been applied to banking, and the use of FTQC quantum computers is required in the banking industry because of the need for rigor

Continue to search for killer applications

- For example, there are no particular issues/concerns at present regarding the optimization of arbitrage at financial institutions, as each financial institution has already been able to do so in its own way.

Future Prospects

Lateral expansion of killer applications

- There are many companies in the financial industry that think "If competitors do work on quantum computers, they could be eliminated from the market because of poor financial services if they don't." and if they find one promising killer application, it is easy for them to expand horizontally.

Collaboration between financial engineering engineers and experts in quantum computer technology

- Through collaboration between engineers working on mathematical optimization and quantum service providers/vendors, etc. search for killer applications

Financial Organize Use Cases

In the field of finance, we were able to confirm use cases mainly for trading of securities financial products and product development and sales of insurance products.

Green text: Use cases added in the second edition.
Underlined: Practical-application use cases.

bank Lending *1	Process	product development	proposals and negotiations	screening and lending	Monitoring and collection
	Use Case	✓ Portfolio optimization of liquid assets	✓ **Application Ad Analysis for Advanced Ad Delivery**	✓ Credit Scoring for SMEs	–
securities Brokerage *2	Process	Product development and sales	orders and contracts	liquidation and delivery	after-sales service
	Use Case	✓ Monte Carlo Simulation for Derivative Pricing	✓ <u>Optimizing stock investment portfolio</u> ✓ Optimization of arbitrage in financial instruments ✓ Estimated Resources Required for Portfolio Optimization ✓ **Financial Transaction Close Forecast**		–
Insurance	Process	Product development and sales	contract and maintenance	insurance payment	after-sales service
	Use Case	✓ <u>Non-Life Insurance Portfolio Optimization</u> ✓ Driving risk prediction based on vehicle sensor data	–	–	✓ <u>Creating optimal work shifts at call centers</u>

*1: In addition to banking business, sales of derivatives and investment trusts are assumed, but the profit ratio is small compared to lending business and securities side discusses it, so it is subordinated.
*2: The securities business is also expected to include dealerships, underriding, and selling, but the overall business flow and the use of quantum computers are expected to remain the same as those of the brokerage business.

Transportation Use Case Trends

In the field of transportation, there are many use cases related to disaster prevention that contribute to solving social issues, and it is expected to be used for saving lives in the future.

Primary use

The main use cases are logistics route optimization, cargo optimization, and optimization of human flow routes.

- Optimization of traffic flow (elimination of traffic congestion), optimization of traffic signals in large cities, optimization of human flow to reduce damage during disasters, etc.

Many areas contribute to solving social issues

- To solve the social issue of "disaster prevention," there are use cases with a sense of social mission such as route optimization in the event of a disaster (flood disaster).

Business Impact and Maturity

Some use cases go to practical use

- There is a use case that has advanced to practical application by utilizing Ising technology.

Adoption challenges

Clarifying the superiority of quantum computers

- As in other areas, it is difficult to demonstrate the superiority of quantum computer technology over conventional methods (classical computers).

On-site coordination, data preparation and standardization

- As in the Discrete Manufacturingarea, there is still room for manpower in this area, and it is necessary to cooperate in the field and prepare and standardize data for practical application.

Future Prospects

It is expected to be used to save lives in the future.

- It is assumed that use cases related to disaster prevention will benefit more from improvements in calculation speed and accuracy than other use cases from the viewpoint of saving lives.

Transportation Organizing Use Cases

In the field of transportation, use cases were confirmed mainly for land transportation targeting humans.

Green text: Use cases added in the second edition.
Underlined: Practical-application use cases.

		Means of transportation		
		land transportation	shipping	air transport
conveyance Subject	human	✓ Traffic flow optimization (congestion reduction) ✓ Optimization of Traffic Signals in Large Cities ✓ Multimodal Transport System Route Optimization ✓ Optimizing human flow for disaster damage control ✓ **Railway scheduling optimization**	–	✓ Traffic control for flying cars (air mobility)
	Mono	✓ Increase efficiency of large-scale logistics ✓ **Optimization of delivery planning** ✓ **Delivery to multiple areas by sharing trucks among multiple stores** ✓ **Optimization of maintenance parts delivery plan**	✓ Sea route optimization ✓ Efficiency of preparation of loading plans for car carriers	✓ Air Cargo Placement Optimization

Energy Use Case Trends

In the energy field, there are many use cases for optimization of power generation, transmission and distribution planning and power consumption planning, and it is expected to be used in electric power market transactions which require a large amount of calculation.

Primary use

Key use cases are optimization of power generation, transmission and distribution planning, and optimization of power consumption planning

- Predicting unstable renewable power output, optimizing supply and demand adjustment of virtual power plants (VPPs), optimizing facility operation planning to reduce power consumption in data centers, etc.

Business Impact and Maturity

At the basic research stage, some advanced companies accumulate technologies and knowledge through demonstration.

- As in the Discrete Manufacturingareas, the focus is on optimization, which is relatively close to practical application, but there are no use cases that have advanced to practical application.
- Some advanced companies conducted VPP operation optimization demonstration (mainly to accumulate technology and knowledge related to quantum computers)

Adoption challenges

Clarifying the superiority of quantum computers

- We are currently developing gate (FTQC) technology with the aim of establishing its superiority over classical computers, and its practical application is expected in 2035 to 40.

Clear validation of user benefits

- For example, optimization of power generation planning and VPP (virtual power plant) operation by electric power companies are seen as promising, but the economic benefits enjoyed by electric power companies when further reduction of calculation time is realized by the introduction of quantum computers have not been clearly verified.

Future Prospects

Expected use in the area of optimizing power market transactions

- In order to optimize electricity market transactions, traders are required to maximize profits by optimizing transactions in the wholesale electricity market, the supply-demand adjustment market, and the capacity market.
- The above optimization calculation is an area of high uncertainty such as policy trends, weather conditions, equipment conditions, risk preferences of traders, and movements of competing traders, and requires a large number of parameters. As the introduction of variable power sources such as renewable energy and storage batteries expands, trading rules in the electricity market are becoming more complex, particularly in Europe and the United States

Energy Organizing Use Cases

In the energy domain, we identified use cases for each of the electricity Processs.

Green text: Use cases added in the second edition.
Underlined: Practical-application use cases.

Process	Electricity Process			
	fuel synthesis	power generation	transmission and distribution	Retailers and customers
Use Case	✓ Nitrogen Fixation Reaction Simulation for Efficient Ammonia Synthesis	✓ Estimation of unstable renewable power output ✓ Optimization of power market transactions	✓ Optimization of Power Distribution Demand Planning ✓ VPP supply-demand adjustment optimization using quantum GAN and QAOA ✓ **Optimization of resource allocation for electricity demand** ✓ **Energy grid optimization**	✓ Optimizing facility operation plans to reduce power consumption at data centers

Combinatorial Optimization Use Case Trends

In the area of combinatorial optimization, there are use cases such as portfolio optimization, production planning optimization, transportation and logistics optimization, and grid optimization. Further practical applications will be advanced by balancing the superiority of classical algorithms with the complexity of operation design and the development of quantum human resources.

Primary use

to be used mainly in manufacturing, transportation and energy sectors

- Specifically, optimization of production planning in the manufacturing industry, optimization of factory layout, optimization of delivery routes and traffic flow in the distribution and transportation fields, and optimization of the balance between supply and demand in the electric power grid.
- What they have in common is that they search for an optimal solution from a large number of combinations, providing more accurate solutions for areas that have traditionally relied on personal experience, intuition, and approximation methods.

Business Impact and Maturity

It is one of the most mature quantum computers, and is not limited to PoC, but will be partially commercialized.

- Direct cost reduction effects are expected, such as reduction in delivery costs by optimizing distribution routes, improvement in utilization rates by optimizing production plans, and improvement in labor efficiency by optimizing personnel shifts. In the financial sector as well, a better balance between risk and return is expected through more sophisticated portfolio optimization
- Also, combinatorial optimization has a relatively high maturity centered on annealing and inspired technologies, and it is an area where the transition from the PoC stage to some actual operations is progressing.

Adoption challenges

Penetration of understanding in sectors where quantum is applied

- Cognitive understanding of the quantum application sector of combinatorial optimization such as the manufacturing industry has not advanced sufficiently. In particular, recognition of the use of quantum computers may be lower than in the fields of pharmaceutical medicine and materials.
- Introduction to the field is an urgent issue for practical use, but no matter how much the management recommends it, practical application will not be realized unless the field agrees.
- In addition, there is a lack of human resources who understand both quantum technology and existing operations, and it is difficult to implement these technologies into actual operations.

Future Prospects

government and industry groups will lead efforts to standardize data across sectors to optimize the entire supply chain

- Required data is closed to the business, and required data is not standardized to optimize the entire supply chain, so we will continue to standardize data across departments and companies across the industry.

Combination Optimization Organizing Use Cases

Combinatorial optimization identified use cases such as portfolio optimization, manufacturing optimization such as factory layout optimization and production planning optimization, transportation and logistics optimization, and grid optimization.

Green text: Use cases added in the second edition.
Underlined: Practical-application use cases.

For each combination optimization Summary	Combinatorial Optimization Types				
	portfolio optimization	manufacturing optimization		transportation and logistics optimization	grid optimization Other
Use Case	✓ Portfolio optimization of liquid assets ✓ <u>Optimizing stock investment portfolio</u> ✓ Optimization of arbitrage in financial instruments ✓ Estimated Resources Required for Portfolio Optimization ✓ <u>Non-Life Insurance Portfolio Optimization</u>	【Plant Layout Optimization】 ✓ Factory Equipment Layout Optimization Using Quantum Computers ✓ Optimizing the Storage and Arrangement of Vehicle Supply Parts at the Parts Center ✓ Optimization of Picking Routes and Shelf Arrangements in Factories and Warehouse ✓ Improve the availability rate of automated guided vehicle (AGV) at factories 【Production Planning and Manufacturing Process Optimization】 ✓ <u>Complex Production Planning Automation</u> ✓ **<u>Improving efficiency of semiconductor manufacturing processes</u>** 【Shift Scheduling Optimization】 ✓ Optimizing Collaborative Shift between Humans and Robots ✓ <u>Creating optimal work shifts at call centers</u> 【Design Optimization】 ✓ **Improving efficiency in automotive computer design**	【Warehouse and Cargo Optimization】 ✓ Air Cargo Placement Optimization ✓ <u>Reducing travel distance for parts aggregation in warehouses</u> ✓ <u>Efficiency of preparation of loading plans for car carriers</u>	✓ Increase efficiency of large-scale logistics ✓ Traffic flow optimization (congestion reduction) ✓ of Traffic Signals in LaOptimizationrge Cities ✓ Multimodal Transport System Route Optimization ✓ Optimizing human flow for disaster damage control ✓ Traffic control for flying cars (air mobility) ✓ Sea route optimization ✓ **<u>Delivery to multiple areas by sharing trucks among multiple stores</u>** ✓ **Railway scheduling optimization** ✓ **<u>Optimization of maintenance parts delivery plan</u>** ✓ **<u>Optimization of delivery planning</u>**	【Power Grid Optimization】 ✓ **Optimization of resource allocation for electricity demand** ✓ **Energy grid optimization** 【Others】 ✓ **Optimization of radio base station settings** ✓ **Improving the efficiency of educational facility development plans**

Simulation Use Case Trends

In the field of simulation, there are use cases such as advanced computer simulations such as CAE, molecular simulation, and financial simulation, and the real value is realized by incorporating quantum computer technology into existing design and development sites/environments.

Primary use

Mainly molecular simulation fields such as material search and drug development. Recently, CAD fields such as structural analysis and fluid analysis and financial simulation such as Monte Carlo simulation have also emerged.

- CAE: Improving jet engine performance, preventing resonance through natural frequency analysis, etc.
- Molecular simulation: prediction of physical properties of materials, analytical simulation of various chemical reactions, molecular simulation of the electronic structure of drug-metabolizing enzymes, etc.
- Financial Simulation: Monte Carlo Simulation for Derivative Pricing

Business Impact and Maturity

Technology maturity is low, but some advanced companies are starting to work on it

- Expected reduction in the number of measures and development lead time due to advanced structural analysis and fluid analysis in CAE
- In addition, complex simulations, such as molecular simulations, which are difficult to perform with classical computers due to computational constraints, are now possible, and innovative results such as the development of new materials and drugs are expected.
- Technology maturity is still low, but some advanced companies have begun to make efforts toward practical use.

Adoption challenges

Development of hardware and algorithms for practical use, and promotion of DX in design and development also

- Quantum computers need to be upgraded to run simulations
- There are very few use cases in actual product design and manufacturing, finance, materials, and drug discovery. This is because, in addition to technical issues due to hardware constraints similar to those in other fields, DX has not advanced in the design and development sites where CAE is expected to be used, and integration with existing tools is difficult.

Future Prospects

Early understanding of users and technical cooperation with overseas universities and research institutes

- The main user in this area is the R & D department, which is already engaged in quantum scientific computing. This leads to understanding and practice of the benefits of introducing quantum computers.
- In the future, collaboration with the world's most advanced researchers will lead to the strengthening of technological and human resources in Japan.

Simulation Organizing Use Cases

Green text: Use cases added in the second edition.
Underlined: Practical-application use cases.

In the area of simulation, we were able to confirm use cases such as structural analysis and fluid analysis in the CAE field, material development and drug development in the molecular simulation field, and Monte Carlo simulation in the financial and market simulation field.

Overview of each simulation	Simulation Type		
	CAE・CFD	molecular simulation	financial and market simulation
Use Case	【Structural Analysis】 ✓ Prevention of Resonance by Natural Frequency Analysis Using Quantum Phase Estimation 【Fluid Dynamics Analysis】 ✓ Optimization of aerodynamic characteristics in aircraft design ✓ Improving Jet Engine Performance	【Materials Development】 ✓ Molecular Simulation for Application to Automotive Material Design ✓ Modeling of Oxygen Reduction Reaction in Automotive Fuel Cell Development ✓ Prediction of material properties and simulation of various chemical reactions ✓ High-precision energy calculation for large-scale molecules and solids ✓ Material property prediction using existing material data × machine learning ✓ Improving the Design of Composite Materials for Aircraft ✓ Nitrogen Fixation Reaction Simulation for Efficient Ammonia Synthesis ✓ **Accelerated platform for material design and reaction analysis** 【Drug Development】 ✓ Molecular simulations of the electronic structure of drug-metabolizing enzymes ✓ Lead compound against Alzheimer's disease-causing enzyme BASE1	✓ **Financial Transaction Close Forecast** ✓ Monte Carlo Simulation for Derivative Pricing

AI Use Case Trends

In the area of AI, use cases such as input of complex data (wave function) using quantum sensors, realization of high-precision machine learning robust to unknown situations, faster inference execution, and low cost and power consumption are being explored.

Primary use

The main use cases are input of complex data (wave function) using quantum sensors, etc., realization of high-precision machine learning resistant to unknown situations, faster inference execution, and low cost and power consumption.

- Higher accuracy in predicting the properties of physical systems using quantum data, communication service fault diagnosis system using quantum kernel learning, cost reduction of LLM in biomedical information analysis, etc.

Business Impact and Maturity

Remain in the technology research and application area design phase utilizing the strengths of quantum computers

- The need for quantum AI technology has not materialized yet, but the technology will be tested for applications that take advantage of the strengths of quantum computers.

Adoption challenges

Establish user benefits

- Promising “faster learning ” has yet to be realized, and other advantages as well as use cases requiring advantages to replace existing AI technologies (e.g., improved response time in automated driving) have yet to be identified.
- Technical maturity and economic impact are unknown as specific use cases are not clear.

Future Prospects

Three possibilities for quantum AI

① A completely new use case based on quantum AI technology (creation of new industries)

② Limited/extreme use cases leveraging quantum AI technologies (e.g., self-driving race cars)

③ Alternative use cases for existing technologies (e.g., data center power savings)

* In this survey, "quantum AI" is defined as AI technology that utilizes quantum computing and performs part or all of the processing (including preparation of learning data) using data representation in quantum states and quantum circuits.

AI Organize Use Cases

In the area of AI, we were able to identify use cases focusing on inference (from inference processing to output).

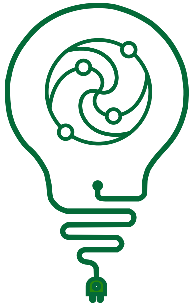
Green text: Use cases added in the second edition.
Underlined: Practical-application use cases.

Process	Learning ~ Reasoning		
	Input (data collection)	model learning	Inference (from inference processing to output)
Use Case	【Input of Complex-Valued Data (Wavefunctions) Using Quantum Sensors and Related Devices】 ✓ Using quantum data to predict the properties of physical systems with higher accuracy 【Generation and Ingestion of High-Quality Random Numbers and Probability Distributions】 ✓ VPP supply-demand adjustment optimization using quantum GAN and QAOA ✓ Credit Scoring for SMEs ✓ **Demonstration of effectiveness of quantum machine learning for quality inspection of agricultural products**	【Achieving Robust, High-Accuracy AI for Unknown Situations】 ✓ Communication Service Fault Diagnosis System Using Quantum Kernel Learning ✓ Improvement of Robot Arm Control Using Quantum Reinforcement Learning ✓ Estimation of unstable renewable power output	【Accelerating Inference Execution and Reducing Cost and Power Consumption】 ✓ Fast Generation of Large Gantt Charts Using a Unique Quantum LLM ✓ Lowering the Cost of LLM in Biomedical Information Analysis ✓ Image Generation Using Quantum Neural Networks ✓ AI Model Compression for 3D Model Conversion of Images Using NeRF Model ✓ Driving risk prediction based on vehicle sensor data ✓ **Application Ad Analysis for Advanced Ad Delivery**
		【Achieving High-Speed, High-Quality Search】 ✓ Proof of Concept of Quantum AI Drug Discovery Process ✓ Development of anticancer drug candidates using quantum AI ✓ **Genome analysis technology using quantum AI**	

Cryptanalysis Use Case Trends

In the field of cryptanalysis, there is a risk that RSA cryptanalysis and elliptic curve cryptanalysis will be decoded. At the present stage, it is assumed that the time to realize such cryptanalysis will be in the medium to long term. However, it is essential to take preventive measures.

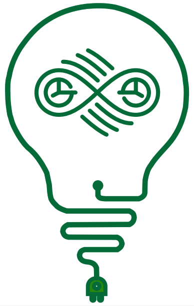
Primary use



Expected a wide range of applications where RSA and elliptic curve cryptography are used

- Among the existing ciphers, RSA ciphers and elliptic curve ciphers are assumed to be decipherable by quantum computers (Shor algorithm).

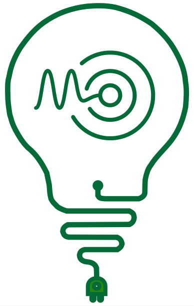
Business Impact and Maturity



Cryptanalysis in the medium to long term

- In the short term, it will be difficult to achieve a quantum computer that can operate stably on a large scale for a long time, and RSA cryptography is expected to be secure for the time being.

Adoption challenges

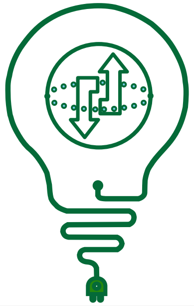


Since there is no roadmap for application on the use case side, it is not clear where measures should be taken first.

- Given the potential for crooks to exploit harvests, cryptography will need to be strengthened long before quantum computers can crack code.
- There is no roadmap for application on the use case side, and it seems to be an issue where measures should be taken first.

*the act of a criminal storing encrypted data in advance and then decrypting and misusing the data after the technology matures in the future

Future Prospects



Quantum-Resistant Computer Encryption, Transition to PQC

- Based on the assumption of a harvest attack, we will identify areas of high priority and take countermeasures.
- High priority The US federal government and NIST standardized public key cryptography (Quantum-Resistant Computer Encryption, PQC) in 2024, which cannot be cracked even by quantum computers, and Google and Apple are already promoting PQC in their products

Chapter 2 List of use cases

List of use cases

Green text: Use cases added in the second edition.
Underlined: Practical-application use cases.

Industry	Method	Use Case	
Manufacturing	Combinatorial Optimization	Air Cargo Placement Optimization	P28
		Complex Production Planning Automation	P30
		Optimizing Collaborative Shift between Humans and Robots	P33
		Factory Equipment Layout Optimization Using Quantum Computers	P35
		Optimizing the Storage and Arrangement of Vehicle Supply Parts at the Parts Center	P39
		Reducing travel distance for parts aggregation in warehouses	P41
		Optimization of Picking Routes and Shelf Arrangements in Factories and Warehouse	P43
		Improve the availability rate of automated guided vehicle (AGV) at factories	P45
		Efficiency of preparation of loading plans for car carriers	P48
		Increase efficiency of large-scale logistics	P50
		Optimization of Decoupling Capacitors in Four-Layer Printed Circuit Boards	P52
		Vehicle design optimization using black box optimization	P54
		Improving efficiency in automotive computer design	P56
		Improving efficiency of semiconductor manufacturing processes	P57
	Simulation	Optimization of aerodynamic characteristics in aircraft design	P59
		Improving Jet Engine Performance	P62

Industry	Method	Use Case	
Process Manufacturing	Simulation	Molecular Simulation for Application to Automotive Material Design	P65
		Modeling of Oxygen Reduction Reaction in Automotive Fuel Cell Development	P67
		Prediction of material properties and simulation of various chemical reactions	P68
		High-precision energy calculation for large-scale molecules and solids	P70
		Material property prediction using existing material data × machine learning	P72
		Improving the Design of Composite Materials for Aircraft	P74
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Drug Discovery and Healthcare	Combinatorial Optimization	Prediction of Allosteric Regulation of Proteins Expansion of drug discovery target	P78
		Search for mid-molecule drug candidates	P80
	AI	Proof of Concept of Quantum AI Drug Discovery Process	P82
		Development of anticancer drug candidates using quantum AI	P84
		Genome analysis technology using quantum AI	P86
	Simulation	Molecular simulations of the electronic structure of drug-metabolizing enzymes	P88
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List of use cases

Green text: Use cases added in the second edition.
Underlined: Practical-application use cases.

Industry	Method	Use Case	
Finance	Combinatorial Optimization	Portfolio optimization of liquid assets	P94
		Optimizing stock investment portfolio	P95
		Optimization of arbitrage in financial instruments	P96
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	Simulation	Monte Carlo Simulation for Derivative Pricing	P106
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Industry	Method	Use Case	
Transportation	Combinatorial Optimization	Traffic flow optimization (congestion reduction)	P109
		Optimization of Traffic Signals in Large Cities	P113
		Multimodal Transport System Route Optimization	P115
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Energy	Combinatorial Optimization	Optimization of Power Distribution Demand Planning	P129
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		VPP supply-demand adjustment optimization using quantum GAN and QAOA	P133
		Optimization of resource allocation for electricity demand	P135
		Energy grid optimization	P137
	AI	Estimation of unstable renewable power output	P138
	Simulation	Nitrogen Fixation Reaction Simulation for Efficient Ammonia Synthesis	P140
		Optimization of power market transactions	P143

List of use cases

Green text: Use cases added in the second edition.
Underlined: Practical-application use cases.

Industry	Method	Use Case	
Others	Combinatorial Optimization	Optimization of radio base station settings	P146
		Improving the efficiency of educational facility development plans	P147
	AI	Using quantum data to predict the properties of physical systems with higher accuracy	P149
		Communication Service Fault Diagnosis System Using Quantum Kernel Learning	P152
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		Lowering the Cost of LLM in Biomedical Information Analysis	P158
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		Demonstration of effectiveness of quantum machine learning for quality inspection of agricultural products	P165
	Simulation	Prevention of Resonance by Natural Frequency Analysis Using Quantum Phase Estimation	P167
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	Cryptanalysis	Evaluation of RSA Cryptanalysis	P170

Manufacturing

Combinatorial Optimization	Air Cargo Placement Optimization	P28
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	Improving Jet Engine Performance	P62

AIRBUS: Air Cargo Placement Optimization [2022/8] 1/2

Industry: Discrete Manufacturing
Process: Procurement
Method: combinatorial optimization

Background

- Airbus expects the global air cargo market to grow 50% by 2042, further exacerbating the emerging supply chain crisis
- Airlines are **seeking to maximize the payload capacity of the aircraft and optimize parameters that affect performance to reduce operating costs (fuel burn)** in order to deliver more efficiently, maximize profits and reduce fuel consumption.
- However, optimization is limited by the range of aircraft operations that need to be complied with.
  - ✓ **The most important limitations are the maximum payload of the aircraft on a particular mission, the position of the centre of gravity of the aircraft on board and the shear limit of the aircraft**
- The roadmaster responsible for the safe loading, transportation, etc. of air cargo is responsible for accurately planning fuel combustion, reducing overall operating costs, and loads (roadsheets) to meet all operational and safety requirements
  - ✓ Traditionally, optimization tasks have been performed manually or through "drag and drop " applications, but the complexity of parameter combinations has limited their use.

Issues and motivation to be solved

- **Optimization problems of cargo placement with an exponential number of combinations are classified as NP-hard problems (exponentially complex problems) and are difficult to solve in a realistic time using classical computers.**
- In 2022, **Airbus partnered with IonQ on a 12-month Quantum Cargo Placement Optimization/Quantum Machine Learning project** to develop prototypes of onboard quantum applications to reduce costs and CO_2 emissions.

Expected business benefits

- In the demonstration, **the optimum arrangement with the maximum loadable weight satisfying the operational constraint including three types of virtual containers was extracted**
  - ✓ **Leverages IonQForte (28 qubits) to perform 250,000 iterations of variational optimization algorithm to** run the math correctly
- This demonstration is the largest optimization algorithm performed on gated quantum systems as of 2023.

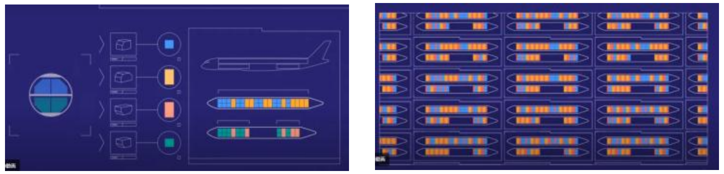
Reference: AIRBUS AIRBUS QUANTUM COMPUTING CHALLENGE (https://www.airbus.com/sites/g/files/jlcbta136/files/2021-10/Airbus-Quantum-Computing-Challenge-PS5.pdf), M e mCoputing Inc "Aircraft Cargo Loading Optimization Case Study" (https://www.memcpu.com/media/2019/04/AirCargo-UseCase-V2.pdf), IonQ"IonQ, Airbus Sign Agreement to Collaborate on Aircraft Loading Project using Quantum Computing" (https://ionq.com/news/august-18-2022-ionq-2022-airbus)

AIRBUS: Air Cargo Placement Optimization [2022/8] 2/2

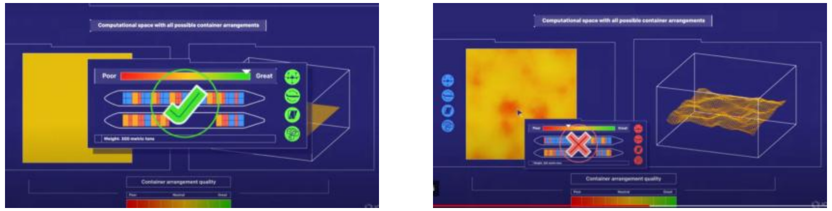
Industry	Discrete Manufacturing
Process	Procurement
Method	combinatorial optimization

Problem setting as a quantum computer

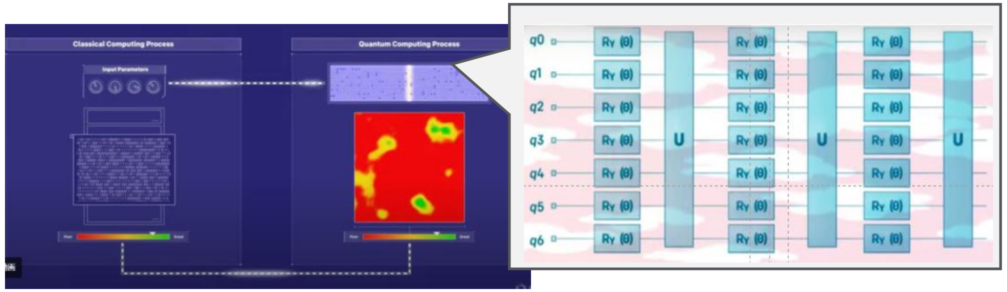
- The **Optimal Placement of Aircraft Cargo** in which there are various slots to hold multiple types of containers becomes a constrained combinatorial optimization problem.
  - ✓ **As constraints, cargo capacity, centre of gravity at maximum cargo mass, shear limits of the aircraft, and virtual containers** are considered**.**
- In quantum computer optimization problems, all combinations of containers and slots can be processed simultaneously in a superposition of qubits.
- Quantum computer calculations search for quantum states that describe the arrangement of containers capable of carrying the heaviest cargo without violating the operational constraints of the aircraft
  - ✓ Variational optimization algorithm identifies container and slot combinations that satisfy constraints and those that do not
- The computation is performed by a combination of the classical computer, which processes input and output data, and the **quantum computer (gated IonQ Forte)** which amplifies the optimum arrangement.
  - ✓ the classical computer selects input parameters that affect the quantum circuit, quantum circuit amplifies the configuration that satisfies the constraints, and sends the result back to the classical computer for evaluation
  - ✓ The above sequence of processes is iterated and finally the operational configuration is extracted as the state of maximum amplitude



Container arrangement in slots of aircraft (left) and combination example (right)



Container placement satisfying constraints extracted by a quantum computer (left) and unsatisfied (right)



Hardware configuration (left) and algorithm (right)
Iteration of input processing by classical computer and large-scale computations by quantum computer

: IonQ"Learn Quantum: Cargo Loading Optimization" (https://ionq.com/resources/learn-quantum-cargo-loading-optimization)

NEC Platforms: Complex Production Planning Automation 1/3【2023/03】

Practical Application

Industry	Discrete Manufacturing
Process	Production
Method	combinatorial optimization

Background

- Due to factors such as high-mix, low-volume production, shortened product life cycles, fluctuating production volumes, and tight supply and demand for semiconductor components, **demand for rapid production of multiple products in response to daily changing demand has become apparent.**
- On the other hand, **To improve productivity, it is essential to improve the efficiency of 'setup' that changes hundreds of types of parts and equipment settings every time a product type is changed. However, since setup itself has no added value, it is necessary to determine whether the complicated setup planning process can be executed in a short time.**
  - ✓ Because the production process time varies greatly depending on the combination of "when" and "in which order" to produce the variety required for that day, which is determined by "arrangement."
- In the past, **skilled workers familiar with the production process devise production plans to minimize setup in response to fluctuations**

Issues and motivation to be solved

- **Due to the increasing complexity of production plans, even skilled workers are currently finding it difficult to make efficient plans** due to high-mix, low-volume production, etc.
  - ✓ In the surface mounting (SMT) process for manufacturing printed circuit boards, mixed production is carried out, in which multiple different types are produced on a single line. However, since "setup" for changing parts and settings is performed by stopping the line, an increase in setup leads to a decrease in productivity.
- **Production planning work was concentrated on skilled workers, but the shortage of skilled workers who are familiar with setup adjustment became apparent due to the decrease in the working population. In addition, existing mechanisms including AI are difficult to automate, and passing on skills is also an issue.**
- In light of the above, NEC Platforms planned to automate production planning by utilizing quantum computer technology capable of high-speed calculations in order to make it possible to revise production plans instantly in the event of sudden configuration changes.

Reference: NEC platforms "Complex Production Planning with Quantum Computing Technology" (https://jpn.nec.com/quantum_annealing/case/necplatforms/index.html)

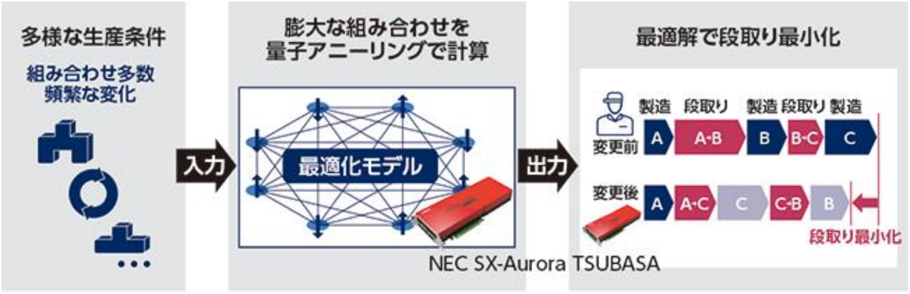
NEC Platforms: Complex Production Planning Automation 2/3【2023/03】

Practical Application

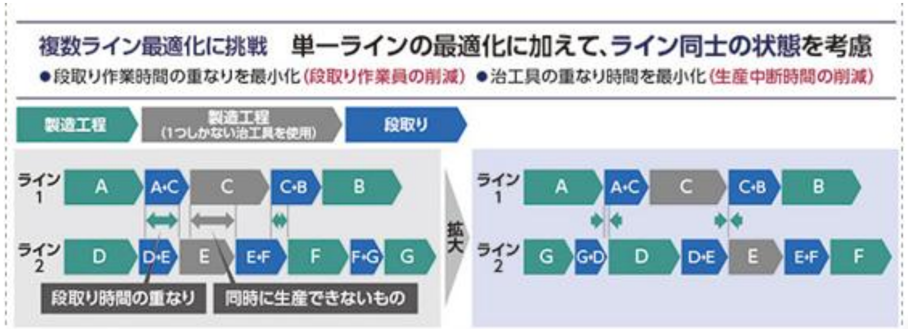
Industry	Discrete Manufacturing
Process	Production
Method	combinatorial optimization

Problem setting as a quantum computer

- Through quantum computer technology, **Automation of production planning to minimize setup and mixed production on multiple lines, *1, Demonstration of high-efficiency production planning in**
  - ✓ **Multi-line x mixed production takes into account resources such as workers and jigs and tools between lines, so it is difficult for a classical computer to process a huge combination of parameters. Therefore, the advantage of a quantum computer capable of simultaneous high-speed processing is utilized.**
- As the objective function, **reduction of setup workers and reduction of production interruption time** is assumed.
  - ✓ Ultra-high-speed processing of large-scale combinatorial optimization problems, such as formulation of delivery plans that minimize delivery distance, time, and cost, and formulation of work shift plans that satisfy job titles and skills, etc.
- Utilization of **NEC Vector Annealing Service** for ultra-high-speed processing of vast combinatorial problems using quantum computing technology
  - ✓ Application of quantum annealing technology to NEC's SX-Aurora TSUBASA vector supercomputer **utilizing quasi-quantum annealing platform**



Optimization of production scheduling of a manufacturing line that leverages the high-speed processing of pseudo-quantum annealing technology



Optimization of mixed production with multiple production lines, which is difficult even for skilled workers

Reference: NEC Platforms "Complex production planning automated with quantum computing technology" (https://jpn.nec.com/quantum_annealing/case/necplatforms/index.html), NEC"NEC Vector Annealing service for solving diversifying business problems as combinatorial optimization problems" (https://jpn.nec.com/nec-vector-annealing-service/index.html)

*1: Mixed production is a system in which multiple varieties are produced on the same line.

NEC Platforms: Complex Production Planning Automation 3/3【2023/03】

Practical Application

Industry: Discrete Manufacturing
Process: Production
Method: combinatorial optimization

Expected business benefits

- Automating production planning by minimizing "setup" and realizing ultra-high-speed simultaneous optimization of multiple lines
  - ✓ **Production planning, which used to take 1~2 hours even for a skilled worker (manual), can be planned with the same accuracy in about 10 minutes.**
  - ✓ In addition, **the simultaneous optimization of multiple lines is more complex, and by shifting the setup time between lines, it is possible to create value-added plans, such as reducing the burden on workers, which was not included in the plans for skilled workers.**
- Production planning automation is expected to reduce setup man-hours by 50%, increase capacity utilization by 15%, and reduce production planning man-hours by 90%.
  - ✓ **Achieve value delivery that leads to overall cost savings with greater scope for optimization**
- **Classical computer AI needs to collect data for machine learning every time a new product is released, but it was not possible to introduce and compare it because the data mentioned on the left was not available.**

Reference: NEC Platforms "Complex production planning automated with quantum computing technology" (https://jpn.nec.com/quantum_annealing/case/necplatforms/index.html), NEC"NEC Vector Annealing service for solving diversifying business problems as combinatorial optimization problems" (https://jpn.nec.com/nec-vector-annealing-service/index.html)

Maxvalu Tokai Groovenotes: Optimizing Collaborative Shift between Humans and Robots 【2023/03】1/2

Industry	Discrete Manufacturing
Process	Production
Method	combinatorial optimization

Background

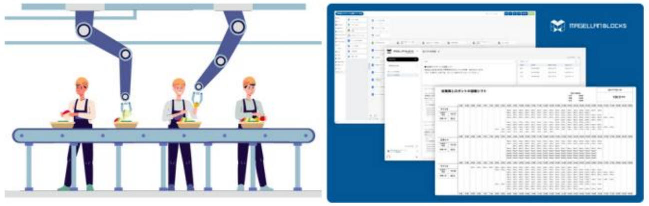
- In production plants, robots are introduced into some of the production processes, and robots and workers are assigned to repeat certain tasks, thereby improving work efficiency.
- On the other hand, **In food factories that produce prepared foods, the objects to be handled are often amorphous, and the introduction of robots is difficult due to the large variety of small lots, and most of the work depends on human hands.**
  - ✓ It is necessary to display irregularly shaped side dishes in a good appearance, but mechanization has not progressed because it is difficult for the same machine to hold sticky potato salad and vinegared dishes with a lot of water to display the specified amount.
- However, amid a labor shortage, **there is a growing need to introduce robots into some of the production processes at delicatessen factories to solve labor shortages through automation and improve production efficiency.**
- The problem lies in **creating optimal shifts for human-robot hybrids.**
  - ✓ **Until now, work shifts at the deli plant have been manually created by plant managers based on their experience.**

Issues and motivation to be solved

- In a factory where humans and robots work together, **it is difficult for humans to create optimal work shifts based on a huge combination of various conditions, such as different working hours and holidays for each employee, differences in work speeds among employees, and robot work capabilities,** and **even a classical computer requires a huge amount of computing resources.**
- Maxvalu Tokai and Groovenotes are working together to **use quantum computer technology to create work shifts combining humans and robots** and to **reduce the workload of employees and improve productivity without increasing the number of employees**.

Expected business benefits

- **Using Magellan Blocks, a quantum cloud platform, we can create an optimal human-robot hybrid work shift in approximately 10 minutes from a vast array of human-robot parameters.**
  - ✓ **The processing time of the quantum computer itself is about 1/100,000 of a second, and the time including the front and back processes such as data acquisition and conversion to shift tables is about 10 minutes.**
  - ✓ Although it has not been put into practical use, the result is not so different from the previous manual shift.



Creating Mixed Man-Robot Work Shifts Using Magellan Blocks Shift Optimization Solution

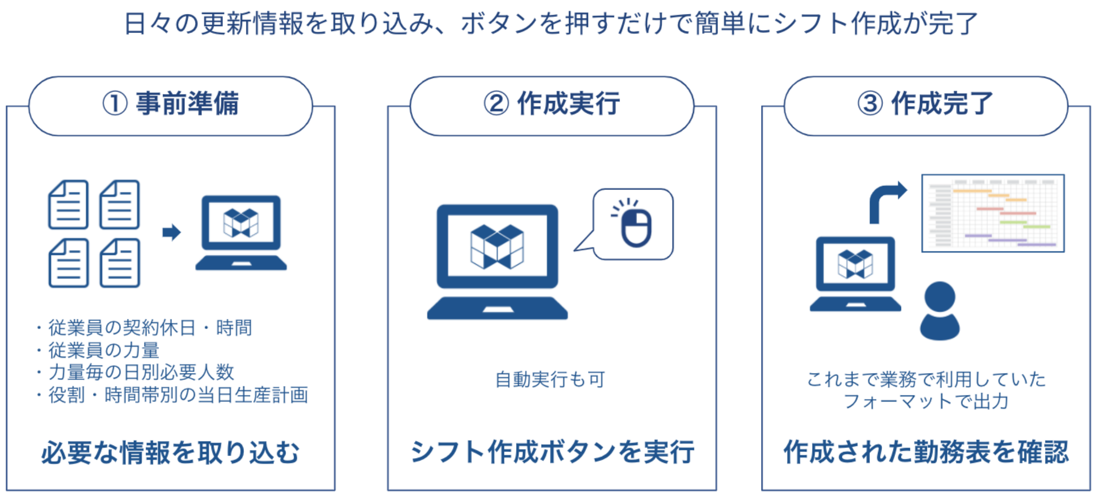
Reference: Sankei Shimbun "Quantum computing could transform work in 10 minutes with cutting-edge technology" (https://www.sankei.com/article/20230602-SRG2QXNDJRJONPFKBPBJKB3FJ4/), Groovenotes Co., Ltd. "Maxvalu Tokai and Gourmet Delica start using shift creation service using quantum computer | Nissay Delica uses AI to predict order volume" (https://www.magellanic-clouds.com/blocks/2022/03/29/robot-friendly-2/), Impress Co., Ltd. "Maxvalu Tokai uses quantum computers to create shifts for deli production" (https://it.impress.co.jp/articles/-/24608)

Maxvalu Tokai Groovenotes: Optimizing Collaborative Shift between Humans and Robots 【2023/03】2/2

Industry	Discrete Manufacturing
Process	Production
Method	combinatorial optimization

Expected business benefits

- Maxvalu Tokai's delicatessen factory needs to deal with a variety of delicatessens
  - ✓ In the case of potato salad with various shapes, softness, and quantity of side dishes handled, it is necessary to deal with multiple cases such as small, medium, large, and increased quantity.
- In the demonstration, **the goal was to automate work shift creation for approximately 50 people, including a potato salad robot line** and **extract industry-common requirements and create an optimization model based on standardized requirements**.
  - ✓ Input data include **the number of employees required by contract hours, holidays, and days, and the amount of prepared food produced per hour as an indicator of employee productivity (the amount that can be served).**
- **Applying the quantum cloud platform 'Magellan Blocks' developed by Groovenotes** to the creation of human-robot hybrid work shifts
  - ✓ Magellan Blocks is a **quantum optimized solution for supply chain management, including production planning, factory logistics, and work shifts.**
  - ✓ The operating environment **utilizes solvers specialized in optimization calculations using D-wave quantum annealing machines and SQBM+ (Toshiba) simulated branching machines**.



Leveraging Magellan Blocks shift optimization solutions
Creation of human-robot mixed work shift

Reference: Sankei Shimbun "Quantum computing could transform work in 10 minutes with cutting-edge technology" (https://www.sankei.com/article/20230602-SRG2QXNDJRJONPFKBPBJKB3FJ4/), Groovenotes Co., Ltd. "Maxvalu Tokai and Gourmet Delica start using shift creation service using quantum computer | Nissay Delica uses AI to predict order volume" (https://www.magellanic-clouds.com/blocks/2022/03/29/robot-friendly-2/), Impress Co., Ltd. "Maxvalu Tokai uses quantum computers to create shifts for deli production" (https://it.impress.co.jp/articles/-/24608)

OKI: Factory Equipment Layout Optimization Using Quantum Computers【 May 2022 】1/4

<u>Industry</u> Discrete Manufacturing
<u>Process</u> process design
<u>Method</u> combinatorial optimization

Background

- **there is a constant labor shortage in the manufacturing industry due to the shrinking domestic labor force**
  - ✓ Labor shortages have become apparent at more than 94% of Japan's large companies and SMEs, and their business has been affected at 32%. *1
- In situations where it is difficult to resolve labor shortages quickly, **increased productivity increases the need to maintain production with limited staff.**
  - ✓ Amid intensifying international competition due to globalization, **it is urgent to improve productivity to reduce manufacturing costs in order to strengthen product competitiveness.**
- **In order to improve productivity in factories, it is necessary to minimize the moving distance (line of movement) of workers by optimizing the arrangement of shelves for storing parts necessary for production equipment and assembly.**
  - ✓ Since the arrangement of shelves and equipment is not based on the work process, **the troublesome movement of workers is a factor of inefficient productivity.**

Issues and motivation to be solved

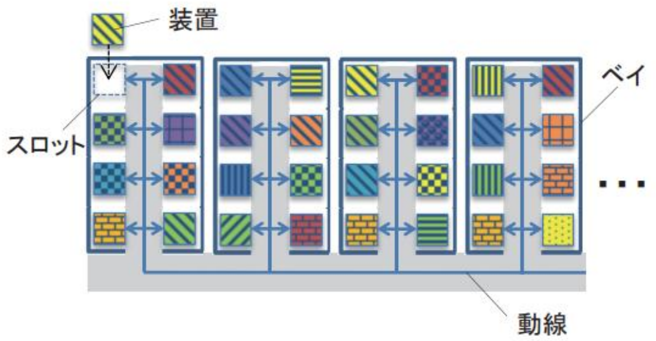
- **As the number and types of equipment increase, the number of combination patterns becomes astronomical, and even with supercomputers, it becomes impossible to calculate the optimal layout when constraints such as the location of equipment are added,** said a factory for precision equipment that combines various types of equipment for production.
  - ✓ OKI's integrated LED plant manufactures multiple products with different manufacturing processes by sharing several hundreds of different types of equipment and having workers move between them.
  - ✓ **Optimal device placement for streamlining requires evaluation of 1,076 combinations, which would take about 1,051 years for a classical computer.**
- **OKI used the D-wave quantum annealer to verify the possibility of shortening the flow line (improving productivity) by calculating the optimum layout of semiconductor manufacturing equipment at its factory.**

Reference: Oki Electric Industry Co., Ltd., "Factory Equipment Layout Optimization Using Quantum Computers " (https://www.oki.com/jp/otr/2020/n235/pdf/otr235_r13.pdf), PR TIMES Co., Ltd. "OKI and OKI Data Apply Quantum Computers to Factory Optimization Problems" (https://prtimes.jp/main/html/rd/p/000000307.000017036.html)
*1: the Ministry of Economy, Trade and Industry: Current situation of labor shortage in manufacturing industry and utilization of foreign human resources, July 12, 2018

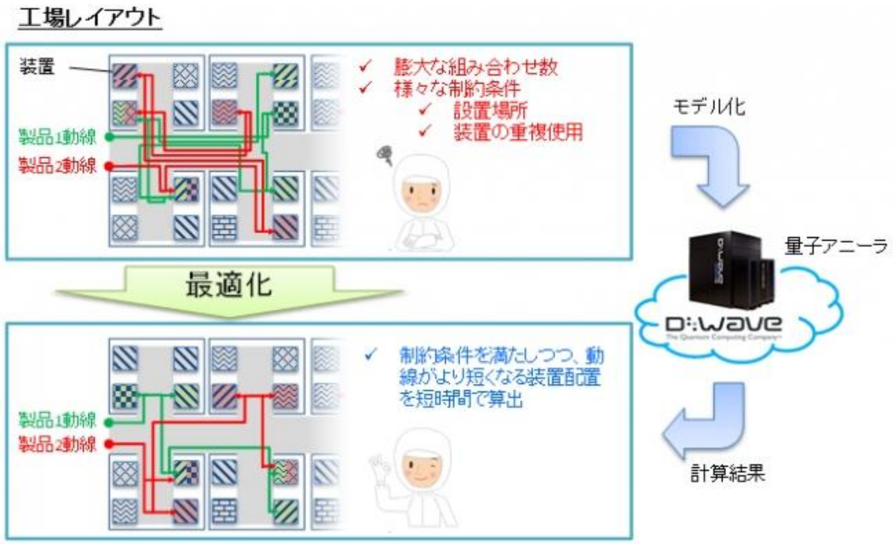
OKI: Factory Equipment Layout Optimization Using Quantum Computers【 May 2022 】2/4

Problem setting as a quantum computer (1/2)

- **OKI's LED factory manufactures several products with different manufacturing processes using partially overlapping equipment.**
  - ✓ The manufacturing process describes the order of the manufacturing process and the equipment used.
  - ✓ The worker processes the parts according to the manufacturing process, moves them to the equipment of the next process, and performs other processes throughout the manufacturing process.
  - ✓ In the factory, a plurality of small rooms (bays) with processing equipment are gathered and formed, and the bays and the equipment in the bays are connected by passageways so that workers can come and go freely.
- The problem of **optimizing equipment placement and minimizing flow lines**. **Since this is a factory that manufactures multiple products, the average value of flow lines of each product is an evaluation index** Defined as
  - ✓ Calculated by weighting each product by the ratio of the number of products manufactured (the ratio of the number of lots) because shortening the flow line of products manufactured in larger quantities contributes to shortening the overall flow line.
- To apply **quantum annealer** to a flow optimization problem **Formulate with QUBO (Quadratic unconstrained binary optimization) model**



factory layout



Schematic diagram of flow optimization (shortening) by quantum annealing

Reference: Oki Electric Industry Co., Ltd., "Optimization of plant layout using quantum computer" (https://www.oki.com/jp/otr/2020/n235/pdf/otr235_r13.pdf)

Problem setting as a quantum computer (2/2)

Problem setting as a quantum computer (Advanced)

problem setting	• Optimize equipment layout to manufacture multiple products and minimize flow lines to complete products
quantum computer Hardware	• Leverage D-wave's cloud platform (Product type unknown)
Implementation	• Perform the following optimization calculations multiple times until the solution converges Run (takes about 30 minutes)
objective function	• distance of the operator's line of motion
Constraints	• Always place one unit per slot (Second Term in Equation (3) in the Right Figure) • One device is always placed in one slot (the third term of equation (3) in the right figure).
Variables	• Unknown number of variables • Exceeds logical variables that can be solved by a D-Wave machine with limits between qubits, so breaks up the problem and iterates

$$x_{s,d} = \begin{cases} 1: スロットsに装置dを配置する \\ 0: それ以外 \end{cases}$$

QUBO variable

$$E(x) = \sum_{u,t,s',s''} x_{s',d_u[t]} \cdot x_{s'',d_u[t+1]} \cdot L(s',s'') + \sum_s \left(\sum_d x_{s,d} - 1 \right)^2 \cdot p + \sum_d \left(\sum_s x_{s,d} - 1 \right)^2 \cdot p \qquad (3)$$

Objective Function of QUBO Model for Minimizing Traffic Line Distance

- S ' and S ' ' are slots in which devices used in the tth and t+ 1th processes are arranged, respectively.
- L(S ', S' ') is the distance between slots S ', S' '
- $d_u[t]$ is the equipment used in the t-th process of product u
- p is the penalty factor

Reference: Oki Electric Industry Co., Ltd., "Optimization of plant layout using quantum computer" (https://www.oki.com/jp/otr/2020/n235/pdf/otr235_r13.pdf)

OKI: Factory Equipment Layout Optimization Using Quantum Computers【 May 2022 】4/4

Expected business benefits

- The equipment arrangement before optimization (present arrangement) was compared with the optimization calculation result, and the quality of shortening of the flow line was evaluated. Calculations are made by **simulating a simulated environment of two products and three lot ratios**.
- Optimization of the equipment **reduces the travel distance of both products.**
  - ✓ The layout is calculated to reduce the flow lines of products with a large number of lots more intensively.
- **A flow line shortening of 20% or more has been realized in all lot patterns.**

(a) ロット数比 (製品1):(製品2)＝1:4

	最適化前	最適化後	増減率
製品 1	1,510	1,284	−15%
製品 2	2,876	2,036	−29%
平均	2,603	1,886	−28%

(b) ロット数比 (製品1):(製品2)＝1:1

	最適化前	最適化後	増減率
製品 1	1,510	961	−36%
製品 2	2,876	2,307	−20%
平均	2,193	1,634	−21%

(c) ロット数比 (製品1):(製品2)＝4:1

	最適化前	最適化後	増減率
製品 1	1,510	832	−45%
製品 2	2,876	2,484	−14%
平均	1,783	1,162	−24%

Results of optimization calculation of flow distance when manufacturing multiple products
(Distance is normalized, so units are arbitrary)

Reference: Oki Electric Industry Co., Ltd., "Optimization of plant layout using quantum computer" (https://www.oki.com/jp/otr/2020/n235/pdf/otr235_r13.pdf)

TOYOTA: Optimizing the Storage and Arrangement of Vehicle Supply Parts at the Parts Center 【2023/12】1/2

Industry	Discrete Manufacturing
Process	process design
Method	combinatorial optimization

Background

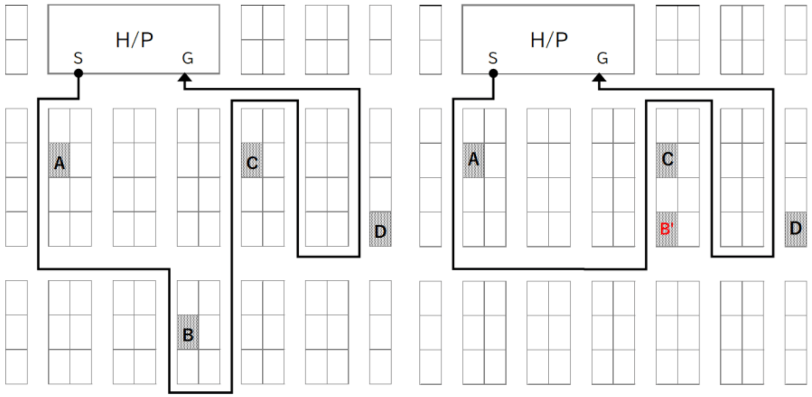
- Toyota has **a wide variety of problems and data on them in various domains (Design, manufacturing, logistics, human resources, etc.)**
- By considering the use of quantum computers for a wide variety of problems, we identify the characteristics of problems that we are good at and bad at.
- By widely sharing the knowledge obtained from the examination results, Toyota hopes to **contribute to the development of quantum technology and solutions to social issues.**

Issues and motivation to be solved

- Combination optimization has been an issue in various areas within Toyota, but **optimization of storage and arrangement of spare parts (parts) for vehicles in parts centers, which is a difficult problem to optimize due to the enormous number of combinations (several billion types)** was selected as a verification issue
- In **picking work** where a worker walks to a storage shelf when an order is received, picks up parts, and returns them, the purpose of this verification is to **reduce the travel distance by changing the storage arrangement of parts.**

Problem setting as a quantum computer

- **The movement distance of the worker was expressed in the form of binary optimization without quadratic constraint which can be handled by the quantum annealer, and the minimization problem of the scale of several tens of thousands variables was solved using this as an objective variable.**
- Tens of thousands of variables are **much smaller than the actual problem,** but **two devices were made to reflect the characteristics of the actual problem as much as possible.**
  - ① Excerpt from the actual shelf layout of the Parts Center
  - ② To generate pseudo order data in which the number of kinds of parts ordered at one time and the distribution of order frequency of each part coincide with actual order data and the number of kinds of all parts is arbitrarily selected.
- The machine uses **D-Wave Systems' Quantum Classical Hybrid Solver Service.**



Reduction of workers' travel distance by changing storage arrangement

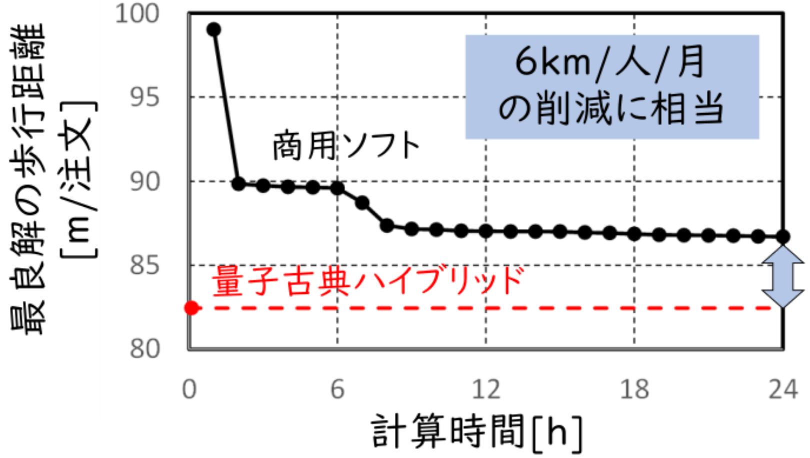
Reference: Toyota Motor Corporation "Quantum computer research at the Mirai Creation Center" (https://global.toyota/jp/mobility/frontier-research/40116331.html)

TOYOTA: Optimizing the Storage and Arrangement of Vehicle Supply Parts at the Parts Center 【2023/12】2/2

Industry	Discrete Manufacturing
Process	process design
Method	combinatorial optimization

Expected business benefits

- Comparison is made between the calculation using commercial optimization software on a classical computer and the quantum classical hybrid calculation.
  - ✓ As a result, **Classical only: 24 hours, quantum classical hybrid: 6 minutes.**
  - ✓ In addition, we were able to calculate **the optimal solution that the quantum-classical hybrid can shorten the walking distance by about 3m**.
- A difference of 3 m can be expected to **reduce the travel distance of 6 km/person per month** if, for example, 1 worker performs picking work 100 times a day and works 20 days per month.



Calculation time and average travel distance

Reference: Toyota Motor Corporation "Quantum computer research at the Mirai Creation Center" (https://global.toyota/jp/mobility/frontier-research/40116331.html)

Fujitsu IT Products: Reducing travel distance for parts aggregation in warehouses 【2018/04】1/2

Practical Application

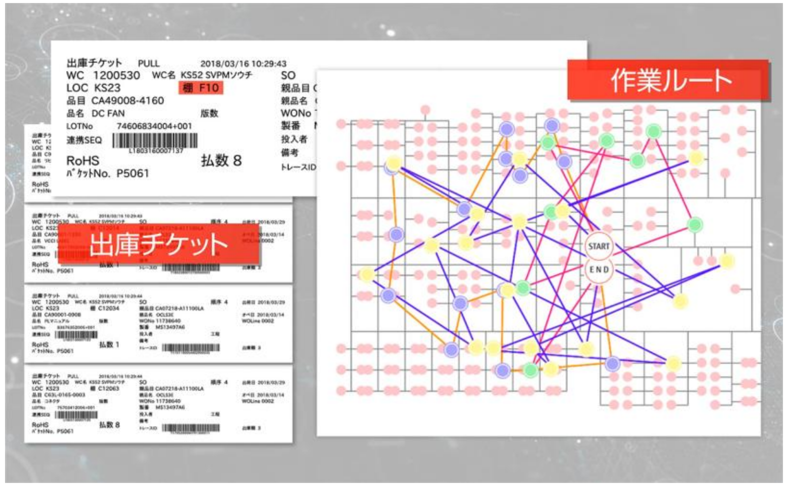
Industry	Discrete Manufacturing
Process	process design
Method	combinatorial optimization

Background

- Fujitsu IT Products manufactures mainframes, UNIX servers, core IA servers, medium and large servers such as supercomputers, and storage systems as Fujitsu's core computer system factory.
- Since its establishment in 2002, the company has been **promoting the rationalization of its production system** under the slogan of **producing a wide variety of products in small quantities** and under the slogan of "Improve customer satisfaction by pursuing QCD(Quality: Quality, Cost: Cost, Delivery: Delivery)"
- As a measure to increase productivity, we have been studying the possibility of utilizing digital annealer by **focusing on the optimization of flow lines in factories including warehouses**

Issues and motivation to be solved

- In warehouse operations, efficient parts picking depends largely on the experience of workers, and inexperienced workers have no idea which parts are on which shelf. **They have to look around the warehouse in vain, and picking takes a considerable amount of time.**
- In recent years, **we had to rely on the experience of veteran workers,** because we had to collect different parts each time because of the large number of kinds of parts delivered by small quantities.
- This time, we **planned to optimize the transportation route** using digital annealer at a Fujitsu IT Products warehouse



Issue ticket (parts list) and work route

Reference: Fujitsu Limited "Up to 45% reduction in travel distance for parts aggregation within warehouses" (https://www.fujitsu.com/jp/digitalannealer/case-studies/201804-fjit/)

Fujitsu IT Products: Reducing travel distance for parts aggregation in warehouses 【2018/04】2/2

Practical Application

Industry	Discrete Manufacturing
Process	process design
Method	combinatorial optimization

Problem setting as a quantum computer

- **Calculate the optimal flow line for picking** at Fujitsu IT Products warehouse (**The area is 1000 square meters and 3000 parts are stored.**)
- A simple single stroke is used as the optimum flow line for picking, and the flow line is visualized on a tablet.
- The machine uses **Fujitsu's quantum-inspired digital annealer**

Expected business benefits

- As a result of the demonstration, the travel distance for collecting parts was **reduced by 20% per month compared with manual labor**.
- And by repositioning shelves, **we expect to see a decrease of up to 45% per month.**
- Rather than telling workers that the flow line has become shorter with just their mouths, it is assumed that by visualizing it on a tablet and letting them know the effect concretely, they will change their consciousness to further improve work efficiency.

Fujitsu IT Products warehouse

displayed on the tablet
optimal picking route

Reference: Fujitsu Limited "Up to 45% reduction in travel distance for parts aggregation within warehouses" (https://www.fujitsu.com/jp/digitalannealer/case-studies/201804-fjit/)

TOPPAN Digital: Optimization of Picking Routes and Shelf Arrangements in Factories and Warehouse 【2024/04】1/2

Industry	Discrete Manufacturing
Process	process design
Method	combinatorial optimization

Background

- Optimizing factory warehouse management is one of the most complex and important challenges.
  - ✓ Optimization helps increase productivity and reduce costs
  - ✓ On the other hand, **poor optimization can lead to increased worker burden, safety issues, and reduced production efficiency.**
- Based on years of experience, the TOPPAN Group has been optimizing picking routes using simulation tools developed in-house
- However, **it was difficult and time-consuming to do the best work in a field that relied on the experience of the workers.**

Issues and motivation to be solved

- The company had been trying to optimize the picking route using in-house developed tools, but it was difficult to optimize the work in the field depending on the experience of experienced workers. Therefore, the company **examined the applicability of quantum technology to the picking optimization**
- **In 2022, Toshiba Digital Solutions launched an initiative to apply quantum-inspired technology to optimize factory and warehouse management** with the aim of enabling efficient operations without depending on the know-how of workers.
- This joint research also tackled **shelf placement optimization in pursuit of picking route optimization**

Expected business benefits

- In addition to optimizing the picking route, the shelf layout was also optimized, resulting in **an average 15% reduction in picking time compared to simulation (classic) with current tools.**
- Expanding the scope of optimization beyond factory and warehouse management to improve BPO and manufacturing processes using quantum technology

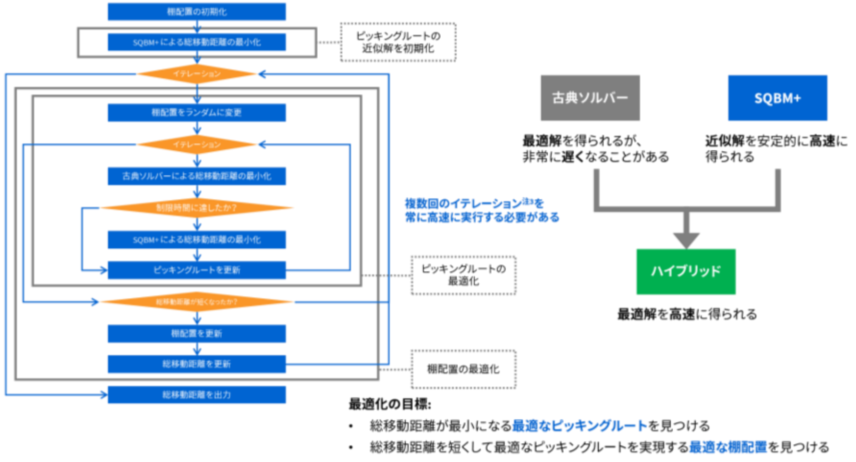
Reference: TOPPAN Holdings Co., Ltd. "TOPPAN Digital and Toshiba Digital Solutions demonstrate the optimization of picking routes and shelf placement in factories and warehouses using SQBM+TM, a quantum-inspired optimization solution." (https://www.holdings.toppan.com/ja/news/2024/04/newsrelease240424_1.html)

TOPPAN Digital: Optimization of Picking Routes and Shelf Arrangements in Factories and Warehouse 【2024/04】2/2

Industry	Discrete Manufacturing
Process	process design
Method	combinatorial optimization

Problem setting as a quantum computer

- Based on the actual data of the TOPPAN Group's factories, an **optimization problem with approximately 9,000 variables** was solved, which was modeled considering items, personnel, areas, and layout elements.
- The objective function is **picking route optimization and shelf placement optimization.**
- The machine uses **SQBM +, a quantum inspired optimization solution from Toshiba Digital Solutions**.
- In order to simultaneously find the optimal picking route and the optimal shelf placement, **a hybrid method that narrows the search range and shortens the search time of the classical solver by using the approximate solution obtained by SQBM+,** utilizing the respective features of SQBM+ and the classical solver.
  - ✓ Features of SQBM +: It can stably generate fast and accurate approximate solutions.
  - ✓ Characteristic of the classical solver: the larger the area searched, the longer the search time and the slower the computation, but the shortest path can be searched



Hybrid solution optimizes picking route and shelf placement

- **目的関数1：ピッキングルートの最適化**

$$F_s(\text{ItemToTask}) = \underset{X,Y}{\text{minimize}} \sum_{w=0}^{\text{NumWorkers}-1} \text{Time}_{s,w}^{Goal}$$

- **目的関数2：棚配置の最適化**

$$G = \underset{\text{ItemToTask}}{\text{minimize}} \sum_{s=0}^{\text{NumSenarios}} F_s(\text{ItemToTask})$$

Modeling

Reference: TOPPAN Holdings Co., Ltd. "TOPPAN Digital and Toshiba Digital Solutions demonstrate the optimization of picking routes and shelf placement in factories and warehouses using SQBM+TM, a quantum-inspired optimization solution." (https://www.holdings.toppan.com/ja/news/2024/04/newsrelease240424_1.html)

Denso/Tohoku University:
Improve the availability rate of automated guided vehicle (AGV) at factories [2019/11] 1/3

Industry	Discrete Manufacturing
Process	Shipping and sales
Method	combinatorial optimization

Background

- **For the manufacturing industry, improving productivity in factories is a priority, and output (quantity and quality) and costs are directly linked to corporate performance.**
- **In the future, with the advancement of smart factories, it will be important to interconnect facilities in factories and IoT, and to visualize in real time the operation status of equipment/production lines, the entire factory, and the entire supply chain including outside the factory, and to manage and control the entire Process.**
  - ✓ At factories, production stoppage, which lasts from several minutes to several tens of minutes, often occurs on a daily basis on each production line. After the production stoppage occurs, workers manually take time to decide whether or not to switch production.
  - ✓ For switching decisions, it is necessary to consider a combination of various parameters, such as the order of assembly of parts and materials, tasks before and after delivery, and milestones. However, classical computers have too many problem scales to optimize them instantaneously.
- The computation time is expected to **slow down the flow of inventory/products and reduce the efficiency of production lines, resulting in significant economic losses**. Specifically, if it is difficult to forecast demand or if a sudden change in the production plan is required, if the production process is not optimized on an ad hoc basis, intermediate inventories tend to increase, which may lead to an increase in costs.

Issues and motivation to be solved

- **The utilization of automated guided vehicles (hereinafter referred to as AGV) is attracting attention for the improvement of production efficiency in factories.** AGVs are automated vehicles for automatically transporting parts and goods within factories and warehouses, **and are an important means of solving problems such as labor shortages.**
  - ✓ AGV contributes to the efficiency of processes between processes and **contributes significantly to the improvement of overall productivity in the plant.**
- On the other hand, since AGVs are usually simple based on predetermined routes and rules, **multiple AGVs trying to travel on the same route may cause congestion,** resulting in **reduced AGV availability.**
- In order to manage and control automated guided vehicles (AGV) and prevent traffic jams, it is necessary to adjust the movements of multiple AGVs traveling simultaneously. Therefore, it is important to provide real-time integrated control of AGVs and **verify the effectiveness of combinatorial optimization to select the optimal path.**
- Denso and Tohoku University conducted a demonstration to improve the availability of AGVs using quantum computers.

Reference: Nikkei BP "Denso's factory AGV route optimization utilization rate increased from 80% to 95%" (https://xtech.nikkei.com/atcl/nxt/column/18/01755/00011/), Business +IT "Why Denso won an acclaim at the world's largest international conference on quantum computers" (https://www.sbbit.jp/article/cont1/35565), Tohoku University "Tohoku University and Denso used quantum annealing machines
Announced efficient delivery technology for automated guided vehicles in factories "(https://www.tohoku.ac.jp/japanese/newimg/pressimg/tohokuuniv-press20191125_01web_Com.pdf)

Denso/Tohoku University:
Improve the availability rate of automated guided vehicle (AGV) at factories [2019/11] 2/3

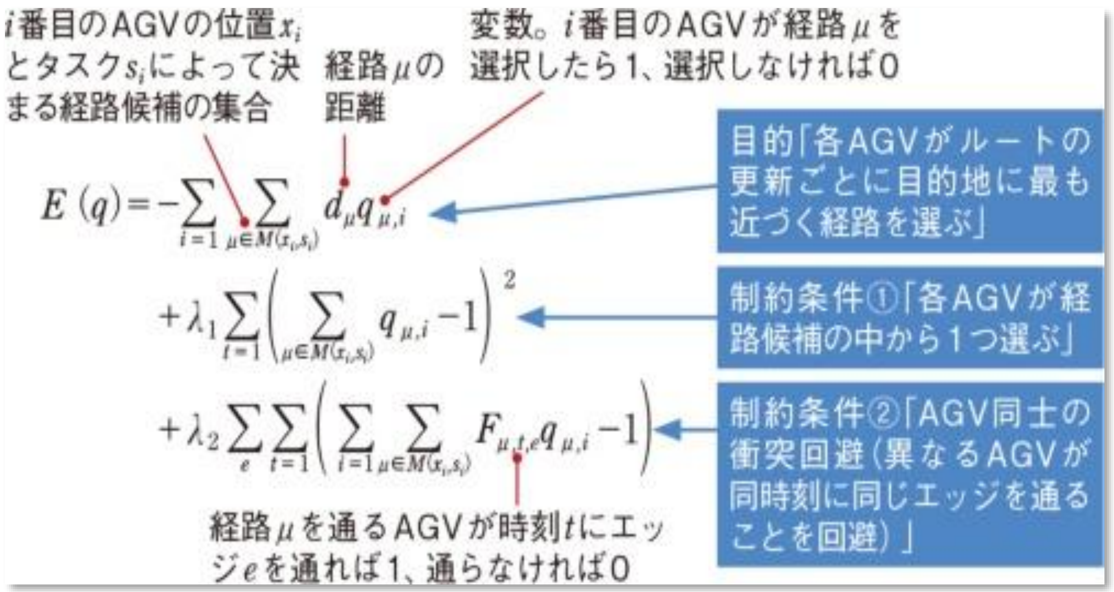
Industry	Discrete Manufacturing
Process	Shipping and sales
Method	combinatorial optimization

Problem setting as a quantum computer

- In this demonstration, we focused on the management and control of the Automated Guided Vehicle (AGV) **and utilized D-Wave's Quantum Annealing Machine as a means of combinational optimization** (instead of optimizing the entire production process in the plant), using an AGV simulator.

Problem setting as a quantum computer (Advanced)

problem setting	• Improvement of operation rate of automated guided vehicles (AGV, Automated Guided Vehicle) at factories
quantum computer Hardware	• D-wave2000Q (2000 qubits)
Implementation	• Update AGV plans with the following optimizations every hour:
objective function	• Reduce AGV downtime as much as possible (i.e. improve utilization)
Constraints	• AGVs must not collide with each other
Variables	• Speed of each AGV (conducted from 10 to 10,000 units) (Select one of three ways: stop, one step forward or two steps forward.)→ Number of combinations is raised to the N-th power of 3 N: Number of AGVs



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Denso/Tohoku University:
Improve the availability rate of automated guided vehicle (AGV) at factories [2019/11] 3/3

<u>Industry</u> Discrete Manufacturing

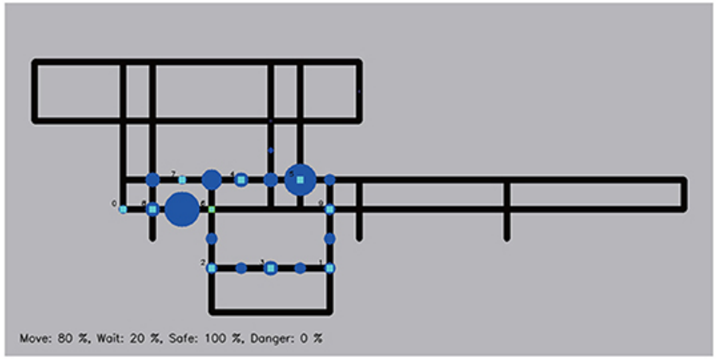
<u>Process</u> Shipping and sales

<u>Method</u> combinatorial optimization

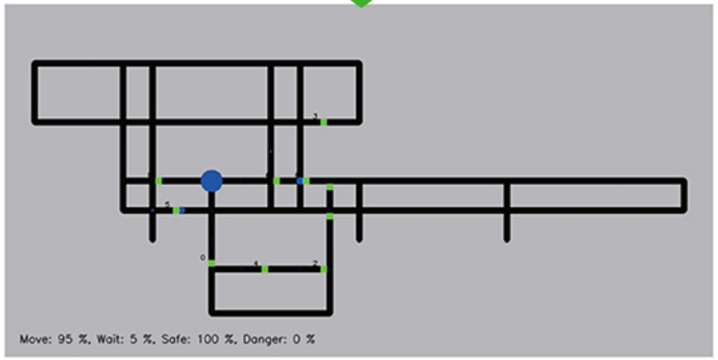
Expected business benefits

- Effect measurement using AGV simulator was verified. The size of the blue circle indicates the number of times the AGV stopped at that point. In other words, **The fewer the blue circles, the higher the utilization rate.**
- **Increased capacity utilization from 80% to 95%** of AGVs. Note that this is a comparison between the no-optimization state (80%) and quantum optimization (95%).

If it works according to existing rules

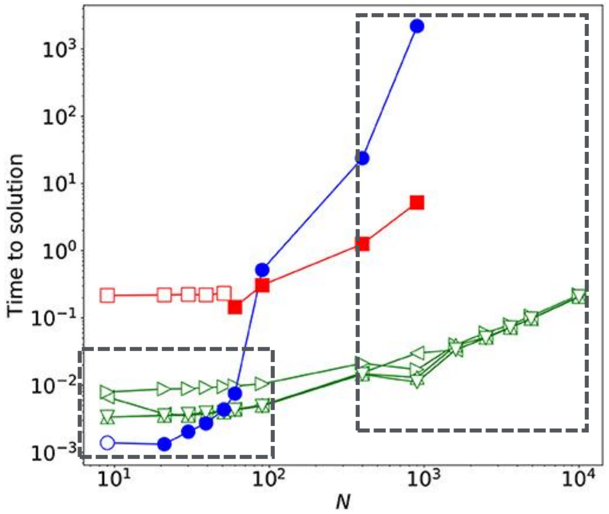


When optimized



Comparison with classical computers

(Comparison based on computation time to find the best solution with 99% probability)



N: Number of AGVs
Above N=60, D-Wave does not work on its own, resulting in hybrid calculations that are dramatically slower due to the overhead involved.

○:D-Wave
□:Digital Annealer
△: Gurobi (done with three options)
Filled means the time to find the best solution with 99% probability;
Time taken to complete solution without fill

Reference: Nikkei BP "Denso's factory AGV route optimization utilization rate increased from 80% to 95%" (https://xtech.nikkei.com/atcl/nxt/column/18/01755/00011/), Business +IT "Why Denso won an acclaim at the world's largest international conference on quantum computers" (https://www.sbbit.jp/article/cont1/35565), Tohoku University "Tohoku University and Denso used quantum annealing machines
Announced efficient delivery technology for automated guided vehicles in factories "(https://www.tohoku.ac.jp/japanese/newimg/pressimg/tohokuuniv-press20191125_01web_Com.pdf)

Nippon Yusen: Efficiency of preparation of loading plans for car carriers 【2021/09】1/2

Practical Application

Industry	Discrete Manufacturing
Process	Shipping and sales
Method	combinatorial optimization

Background

- Nippon Yusen is developing a global automobile transportation business by carrying thousands of vehicles on a single automobile carrier to connect Japan with other parts of the world.
- On a car-only ship, **cars are loaded one by one at fixed intervals according to a predetermined loading plan, but the number of possible loading methods is enormous.**
  - ✓ For example, when a car carrier with a maximum loading capacity of approximately 7,000 vehicles and 12 floors calls at more than 10 ports and loads and unloads more than 60 types of vehicles of different heights and widths, **the number of candidate vehicle loading methods is 10 to the power of 2,000 or more.**
- **It is a very complex task to create a stowage plan that meets the constraints,** such as loading vehicles at a loading rate close to the maximum capacity of the ship and ensuring safe space for loading and unloading.

Issues and motivation to be solved

- Conventionally, specialized planners made a stacking plan by mastering stacking patterns and arrangement methods through experience.
- **Various issues have long been involved in the efficient preparation of stowage plans.**
  - ✓ Individual differences in the quality of the stacking plan occur depending on the experience and skill of each planner.
  - ✓ Planning time per ship is up to about six hours.
  - ✓ The change of the stacking schedule due to the sudden change of the situation causes a heavy workload.

car ship

Reference: FUJITSU CORPORATION "Digital Anilla" to Improve Efficiency of Preparation of Loading Plans for Automobile Carriers "(https://pr.fujitsu.com/jp/news/2021/09/2.html)

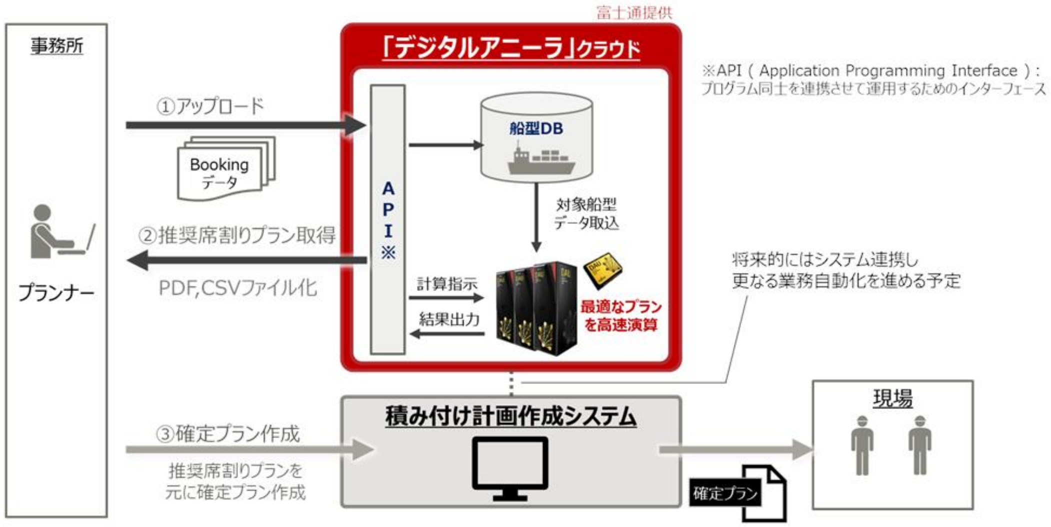
Nippon Yusen: Efficiency of preparation of loading plans for car carriers 【2021/09】2/2

Practical Application

Industry	Discrete Manufacturing
Process	Shipping and sales
Method	combinatorial optimization

Problem setting as a quantum computer

- **We take in information about the size of the vehicle to be loaded and the port to be unloaded from Nippon Yusen's internal system, and use a digital annealer to make the best fit.**
  High-speed calculation of loading position was performed.
- As a result, **a system has been constructed on the cloud that automatically completes in about 30 minutes** the most important task of creating a stowage plan, which is to plan the optimal loading position of a vehicle in consideration of various conditions.
- The machine uses **Fujitsu's quantum-inspired digital annealer**



system schematic diagram

Expected business benefits

- Veteran planners **reduced the number of hours needed to prepare a loading plan (manpower) from a maximum of about 6 hours to about 2.5 hours** per ship.
- This saved planners **more than 4,000 hours a year** in stowage planning time
- As a side effect of the time reduction, the following is expected
  - ✓ Expanding business opportunities with faster decision making
  - ✓ Realize more efficient response to sudden changes in plans
  - ✓ Reduce variations in the quality of stacking plans due to differences in planners' experience

Reference: FUJITSU CORPORATION "Digital Anilla" to Improve Efficiency of Preparation of Loading Plans for Automobile Carriers "(https://pr.fujitsu.com/jp/news/2021/09/2.html)

Toyota Systems: Increase efficiency of large-scale logistics【2020/09】1/2

Industry	Discrete Manufacturing
Process	Shipping and sales
Method	combinatorial optimization

Background

- In recent years, the importance of logistics has increased as an infrastructure that supports society, but there are a variety of issues
  - ✓ Driver shortage, traffic congestion, increased CO2 emissions, etc.
- On the other hand, **distribution management of necessary parts to factories** is the basis of the supply chain, and further **efficiency improvement and cost reduction** are required.
- Toyota Systems was established in January 2019 as an IT solutions company to support Toyota Motor Corporation and its group companies with technological capabilities and productivity. Since 2018, Toyota Systems has been conducting research with Fujitsu on the application of quantum computing.

Issues and motivation to be solved

- In the logistics industry, **the conventional (classical) method (conventional optimization engine) requires enormous calculation time as the problem size increases, and manual adjustment is required.**
- Concerning automobile manufacturing, we planned to **apply Fujitsu's digital annealer to calculate the effect on a large-scale logistics network with more than 3 million possible routes.**

Expected business benefits

- As a result of simulation (trial calculation), we were able to **calculate in less than 30 minutes a new route that can reduce the total logistics cost** from more than 3 million possible routes (we discovered an effective logistics route that had not been found before).
- In addition, we expect **a cost reduction effect of approximately 2~5% compared to the conventional method (classic).**

Reference: Fujitsu Limited "Toyota Systems and Fujitsu Prove Efficiency of Large-Scale Logistics Using Digital Annealer" (https://pr.fujitsu.com/jp/news/2020/09/10-1.html)

Toyota Systems: Increase efficiency of large-scale logistics【2020/09】2/2

Industry: Discrete Manufacturing
Process: Shipping and sales
Method: combinatorial optimization

Problem setting as a quantum computer

- Of more than 3 million distribution routes, **the route with the lowest distribution cost** was calculated.
  - ✓ It is assumed that parts will be purchased from more than hundreds of suppliers and delivered to dozens of factories through several intermediate warehouses.
  - ✓ Logistics costs were calculated based on the number of trucks, the total distance traveled, and the amount of cargo sorting work.
- In order to apply the system to actual logistics operations, we developed a system incorporating the following two technologies and applied them to the demonstration.
  - ✓ global search technique: a technique to search a wide area while efficiently escaping from a local solution group
  - ✓ Dynamic multipoint search technology: A technology that dynamically determines the starting point according to the status of the search
- The machine uses **Fujitsu's quantum-inspired digital annealer**

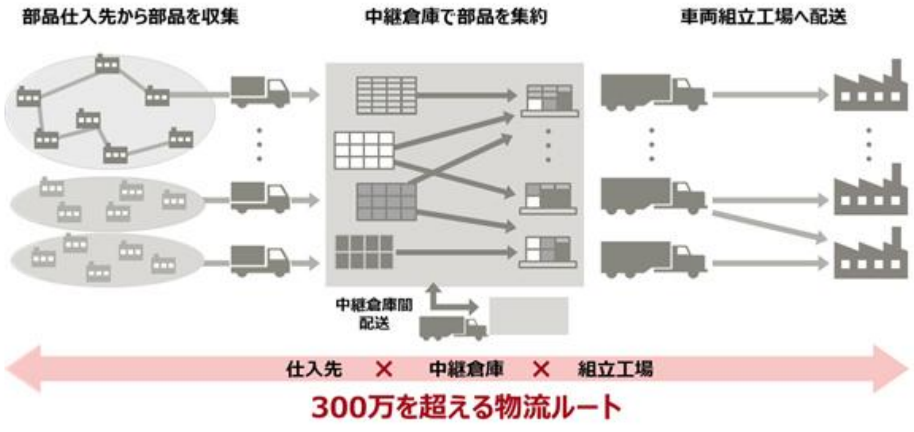
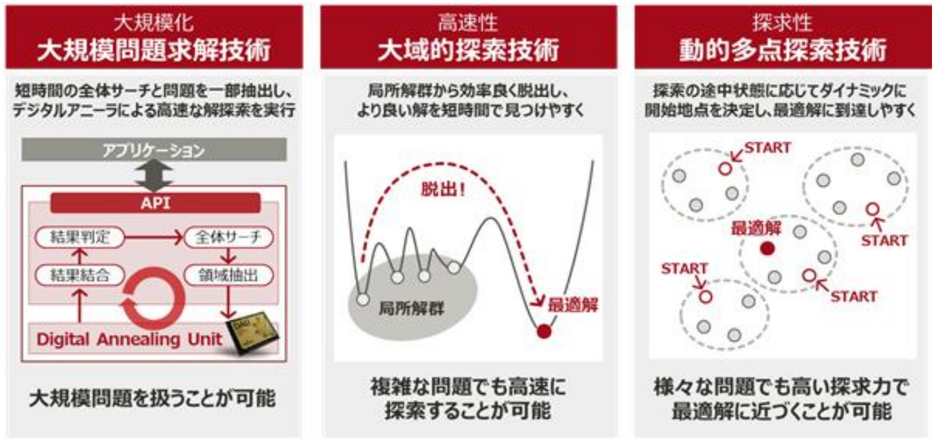


Image of Large-Scale Logistics Network



solution technology of digital annealer

Reference: Fujitsu Limited "Toyota Systems and Fujitsu Prove Efficiency of Large-Scale Logistics Using Digital Annealer" (https://pr.fujitsu.com/jp/news/2020/09/10-1.html)

Fujitsu: Optimization of Decoupling Capacitors in Four-Layer Printed Circuit Boards 【2024/3】1/2

Industry	Discrete Manufacturing
Process	R & D and product design
Method	combinatorial optimization

Background

- Fujitsu has released a fourth-generation digital annealer using its own technology. **Digital annealer is a computing technology inspired by quantum phenomena that can quickly solve combinatorial optimization problems that are difficult to solve with ordinary computers.**
  - ✓ Large annealing cores implemented on multiple GPUs
- Electromagnetic interference (EMI) is defined as **electromagnetic interference** or "radio wave interference, in which electromagnetic waves emitted by electronic or communication devices have an impact on other devices or systems.
- **In this project, EMI is evaluated to identify the capacitor combination that produces the smallest radiated electric field.**

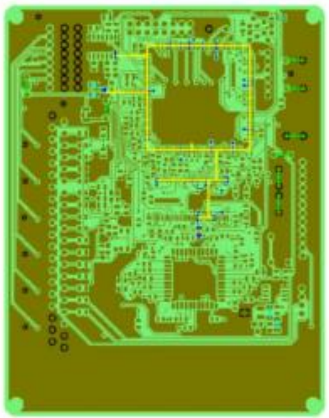
Issues and motivation to be solved

- **Large-scale calculations are required to optimize the number and capacitance of decoupling capacitors for noise reduction. For example, if there are 38 capacitors and no capacitance or 7 levels of capacitance, a total of 2.07×1034 combinations are generated.**
- **Design optimization achieved by reducing the number of capacitors while reducing noise electrolysis**

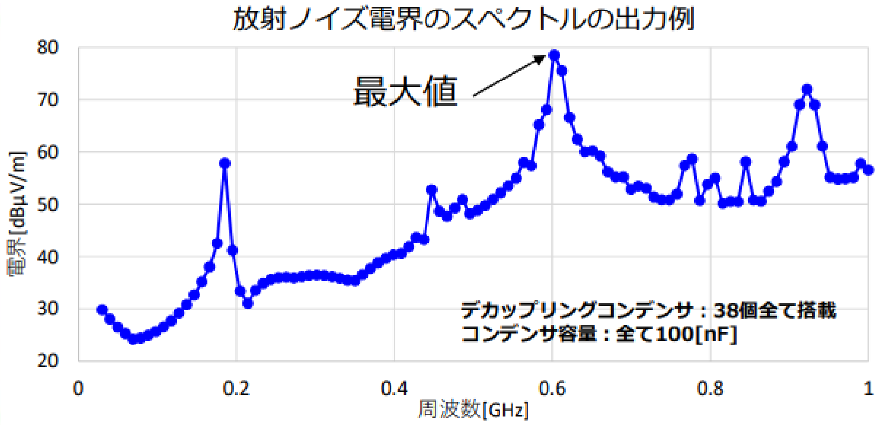
Problem setting as a quantum computer

- Electromagnetic field analysis was performed and the design was optimized by **high-speed search on approximate model by FM-DA and global search by GA (genetic algorithm),** *1 and), which combined digital annealer and machine learning. On a 121 × 94 × 1 [mm] substrate, 650,000 steps were performed with 50.4 million gratings, and as a result of analysis, an output of the 10 m method radiation electric field (30 MHz to 1 GHz) was obtained.
- **QUBO Formulation**, *2 and **Automatic Generation by Machine Learning** Required for Digital Annealer
- HW utilizes Fugaku and Fujitsu's proprietary large-scale annealing core technology

*1: Genetic algorithm is an algorithm that searches for an approximate solution based on the concept of evolutionary theory.
*2: QUBO formulation refers to the formulation as a quadratic polynomial of binary variables feasible for quantum annealing



analytical model



analysis result
(10 m method: Emission electric field (30 MHz to 1 GHz))

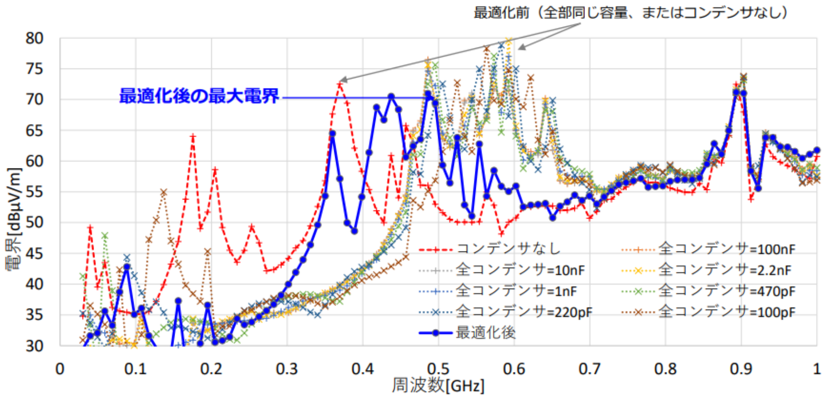
Reference: Fujitsu Limited, "Up to this point, HPC✕ Electromagnetic Field Analysis" (https://www.hpci-office.jp/documents/workshop/cae-ws.240308_Kochibe.pdf)

Fujitsu: Optimization of Decoupling Capacitors in Four-Layer Printed Circuit Boards 【2024/3】2/2

Industry	Discrete Manufacturing
Process	R & D and product design
Method	combinatorial optimization

Expected business benefits

- For a 4-layer printed circuit board, the maximum electric field value of 72.52~79.55 [dBμV/m] was reduced from 38 capacitors before optimization to **20 capacitors 71.18 [dBμV/m],** reducing the number of capacitors by approximately half while suppressing the noise electric field.



Optimization Results by FMDA+GA

C9000	C9001	C9002	C9004	C9005	C9006	C9009	C9011	C9014	C9016	C9017	C9019	C9021	C9022	C9023	C9024	C9027	C9028	C9029
なし	10nF	1nF	100nF	なし	1nF	なし	1nF	100pF	なし	1nF	100pF	1nF	なし	なし	なし	470pF	なし	なし
C9030	C9035	C9036	C9043	C9044	C9047	C9048	C9057	C9058	C9069	C9070	C9071	C9072	C9073	C9074	C9075	C9076	C9077	C9078
なし	なし	100pF	10nF	100pF	1nF	なし	なし	なし	2.2nF	なし	2.2nF	なし	2.2nF	なし	なし	220pF	220pF	470pF

Optimization result of capacitor presence and capacitance value

Reference: Fujitsu Limited, "Up to this point, HPC✕ Electromagnetic Field Analysis" (https://www.hpci-office.jp/documents/workshop/cae-ws.240308_Kochibe.pdf)

Mazda: Vehicle design optimization using black box optimization [2024/9] 1/2

Industry: Discrete Manufacturing
Process: R & D and product design
Method: combinatorial optimization

Background

- Since 2006, Mazda has been working to **share the optimal structure across models and grades** based on its Common Architecture strategy
- **Black box optimization using quantum annealing Ising machine was utilized for the design of optimum structure exceeding car models (optimization of thickness of steel plate).**
  - ✓ From 2014 to 2015, Mazda, in collaboration with JAXA and the Tokyo University of Science, tried an approach to optimizing the thickness of steel plates using a supercomputer based on evolutionary calculations. However, it took tens of thousands of trials and several months to obtain a reasonable Pareto solution with conventional techniques, and it became clear that further efforts were needed for practical application.

Issues and motivation to be solved

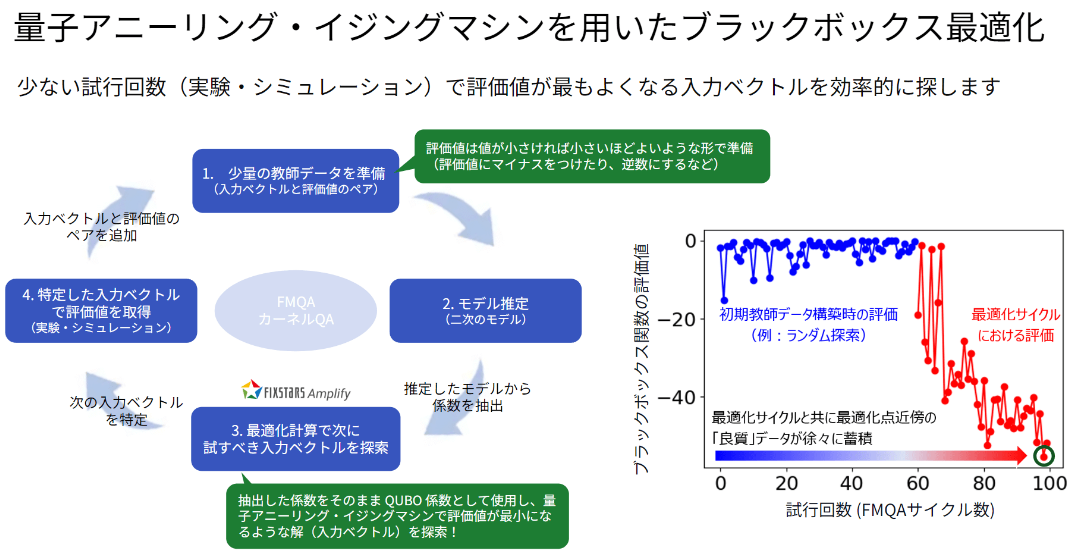
- Mazda addressed the simultaneous optimization problem of body structure design by Bayesian optimization, but **the problem remains that it becomes extremely difficult to find a solution that satisfies the constraints, especially as the size of the problem increases.**
- Regarding the above issues, we implemented initiatives with the aim of achieving FMQA [*1], **black box optimization by,** [*2] and **solution by**.

*1: Black-box optimization method combining machine learning and quantum annealing

*2: Optimize (minimize/maximize) the result for a given input in a situation where only the output result can be obtained and no other information is given.

Problem setting as a quantum computer

- As a simultaneous optimization problem of body structure design for 3 models, the **problem of determining which thickness of steel plate is best allocated** was addressed to 74 parts per model (222 parts in total for 3 models). After satisfying the constraints on quality characteristics such as ride comfort and collision performance required for each model, the **multi-objective optimization problem of realizing vehicle weight reduction and maximizing the number of parts common to multiple models** was tackled.



Optimization by FMQA

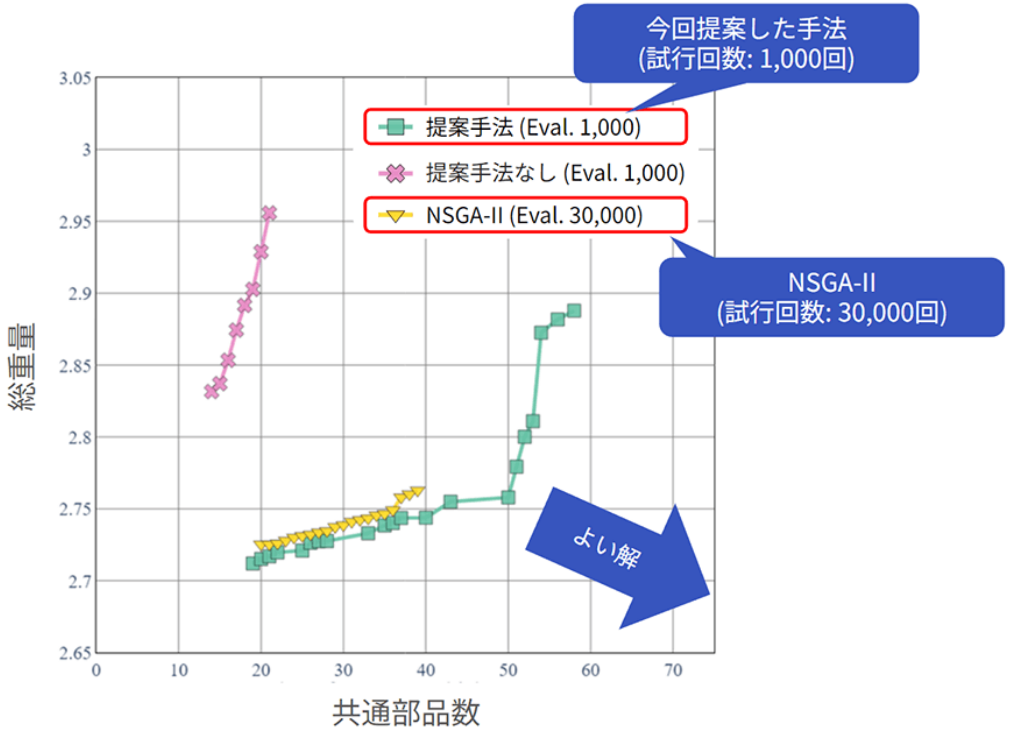
Reference: Fixstars Amplify “Mazda Motor Corporation Black Box Optimization for Vehicle Design ” (https://amplify.fixstars.com/ja/customers/interview/vehicle-co-optimization)

Mazda: Vehicle design optimization using black box optimization [2024/9] 2/2

Industry	Discrete Manufacturing
Process	R & D and product design
Method	combinatorial optimization

Expected business benefits

- Optimization using a black box using a quantum annealing ising machine **succeeded in obtaining a solution superior to that obtained by NSGA-II after 30,000 trials in 1,000 trials**, which is one of evolutionary calculations and a representative method of multi-objective optimization
- At present, it is in the research stage, and the main focus was on how quickly a good solution could be found. However, **it is necessary to be able to stably obtain a moderate solution in a small number of trials, even if it is not the best solution for daily use in the field of actual design.**
- In addition, it is necessary to make systems and parameterless systems that are easy to use by any designer.



superiority of the proposed method
(Weight reduction in complex conditions with many parts)

Reference: Fixstars Amplify "Mazda Motor Corporation Black Box Optimization for Vehicle Design " (https://amplify.fixstars.com/ja/customers/interview/vehicle-co-optimization)

Fujitsu and Toyota Systems: Improving efficiency in automotive computer design【2026/1】

Industry	Discrete Manufacturing
Process	process design
Method	combinatorial optimization

Background

- The mobility industry needs to address sustainable product development and increasingly complex software and hardware designs, but **there is a serious shortage of human resources to support them.**

Issues and motivation to be solved

- **The connector pin arrangement of the in-vehicle computer has a scale of 100 pins, and theoretically there are 9.3×10 to the power of 157 combinations. This is a problem that takes time to study and decision making is easy to become personal.**

Problem setting as a quantum computer

- The AI model learns information obtained by scoring the connector pin placement pattern and its evaluation, which had been determined based on the knowledge and know-how of skilled engineers, and converts the AI model into mathematical expression information.
- **Constructed a mechanism to automatically calculate the optimal placement of connector pins through high-speed calculation processing using quantum inspired optimization (Fujitsu Digital Annealer).**

Expected business benefits

- High-speed calculation by digital annealer achieves **20 times faster than conventional**
  - Costs are expected to be reduced by reducing design man-hours and suppressing redesign and troubleshooting.
- It is expected that skilled know-how, which has been a subject of personal development, will be transformed into formal knowledge, and that it will also address issues related to technology succession.

Image of efforts to improve design efficiency

Reference: Toyota Systems Incorporated and Fujitsu Limited: "Toyota and Fujitsu use quantum-inspired technology, AI to streamline automotive computer design for sustainable development" (https://global.fujitsu/ja-jp/pr/news/2026/01/14-01)

ROHM, Quanmatic:
Improving efficiency of semiconductor manufacturing processes [2025/7] 1/2

Practical Application

Industry: Discrete Manufacturing
Process: Production
Method: combinatorial optimization

Background

- In the semiconductor industry, **the number of combinations increases exponentially with larger manufacturing processes, and the number of constraints makes it difficult to obtain an optimal solution.**
- **In the EDS process, too, the number of combinations of manufacturing devices, test equipment, test conditions, etc. is enormous, and it was** very difficult **to derive a solution to optimize the manufacturing process even for a part of the process.**
- Conventionally, operations (process allocation) were performed based on basic calculation rules and utilizing accumulated knowledge and know-how.

Issues and motivation to be solved

- **Reduction of loss during EDS process setup, improvement of equipment availability and throughput, and enhancement of stable supply system**
- Taking advantage of the world's first full-scale introduction of quantum technology at a large-scale plant, we are expanding to more complex areas, including front-end processes, and optimizing the entire supply chain.

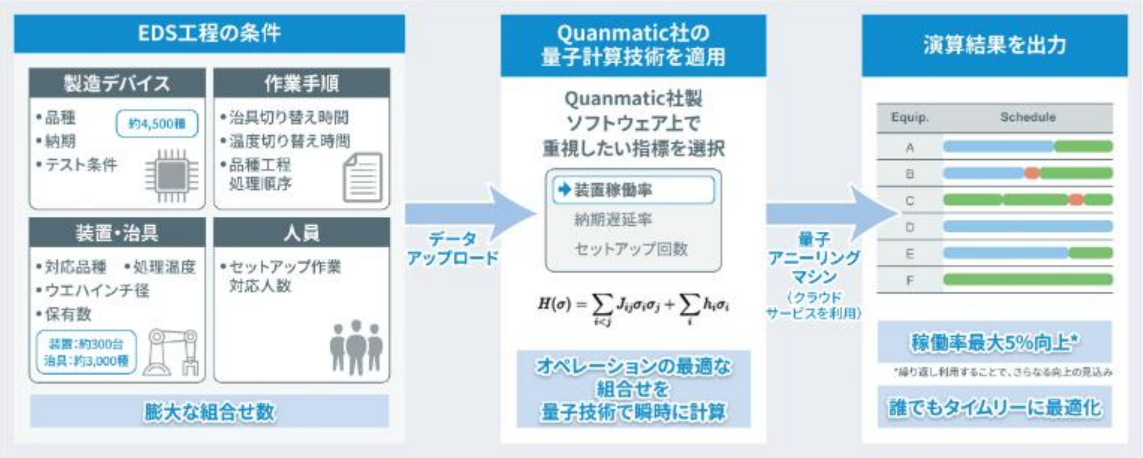


Image of Semiconductor Manufacturing Process Efficiency

Reference: ROHM Co., Ltd. and Quanmatic Co., Ltd.: "Rohm and Quanmatic use quantum technology to improve semiconductor manufacturing efficiency" (https://quanmatic.com/news/semiconductor-efficiency-quantum-tech/)
ROHM Co., Ltd.: "Rohm and Quanmatic complete verification of manufacturing process optimization using quantum technology The world's first achievement in a large-scale semiconductor manufacturing plant, aiming for full-scale introduction of the EDS process in April 2024" (https://www.rohm.co.jp/news-detail?news-title=2023-12-05_news&defaultGroupId=false)

ROHM, Quanmatic:
Improving efficiency of semiconductor manufacturing processes [2025/7] 2/2

Practical Application

Industry	Discrete Manufacturing
Process	Production
Method	combinatorial optimization

Problem setting as a quantum computer

- Introducing an optimized computing system that combines Quanmatic's product group for improving the efficiency of quantum computing technology based on research at Waseda University and Keio University, a computational framework that utilizes quantum and classical computing technology, and specialized formulation technology with ROHM's vast knowledge, know-how, and various data.

Expected business benefits

- **By applying quantum technology to the EDS process, which is part of the semiconductor manufacturing process, losses during setup were successfully reduced by 40% compared to conventional methods.**
- **This is the world's first full-scale introduction of quantum technology in a large-scale semiconductor manufacturing process and one of the largest examples of improvements achieved.**
  - A demonstration test was successfully conducted in some areas of ROHM Hamamatsu in April 2025, and studies are underway for full-scale introduction in the future.
- They also discussed the possibility of introducing an optimized calculation system using quantum technology to a larger and more complex previous process. **By utilizing the knowledge gained through demonstration and introduction in the EDS process, we succeeded in an effective construction in a short period of time, and a prototype was completed in January 2025.**

Reference: ROHM Co., Ltd. and Quanmatic Co., Ltd.: "Rohm and Quanmatic use quantum technology to improve semiconductor manufacturing efficiency" (https://quanmatic.com/news/semiconductor-efficiency-quantum-tech/)

Airbus: Optimization of aerodynamic characteristics in aircraft design [2020/11] 1/3

Industry	Discrete Manufacturing
Process	R & D and product design
Method	Simulation

Background

- The shape and design of the entire airframe of an aircraft are important factors in airframe design because they affect energy efficiency.
- At present, **CFD**, *1, and **are utilized to determine an airframe shape with high efficiency**, and **aerodynamic characteristics evaluation to analyze the air flow around the airframe and elucidate the forces exerted on the airframe** are being conducted
  - ✓ Aircraft is considered to be a factor of global warming because it emits a large amount of carbon dioxide. Therefore, the aircraft industry is required to optimize airframe design and aircraft operation.

Issues and motivation to be solved

- **A supercomputer is used to model the air flow around the airframe and evaluate the aerodynamic characteristics, but the processing time is long and it is difficult to improve the accuracy.**
- With the aim of utilizing quantum computers that can perform large-scale and high-speed calculations in aircraft design, Airbus held the **Quantum Computing Challenge** *2 and **NISQ** in 2019 to compete on tasks to improve aircraft design efficiency.
- In the Challenge, Origin Quantum, a Chinese quantum computer HW vendor, was selected as a finalist for the evaluation of aerodynamic characteristics using quantum computers.
- **Origin Quantum ran an aerodynamic evaluation model on a quantum computer to verify the possibility of fast computation**

*1: CFD is a numerical analysis and simulation method that observes the flow by solving equations related to the motion of a fluid (Euler equations, Navier-Stokes equations, or their derivatives) on a computer using the numerical solution of partial differential equations, etc.

*2: In the Quantum Computing Challenge, in addition to evaluating aerodynamic characteristics, five tasks were set, including optimization of aircraft cargo placement and wing structure, and finalists were selected for joint research with Airbus.

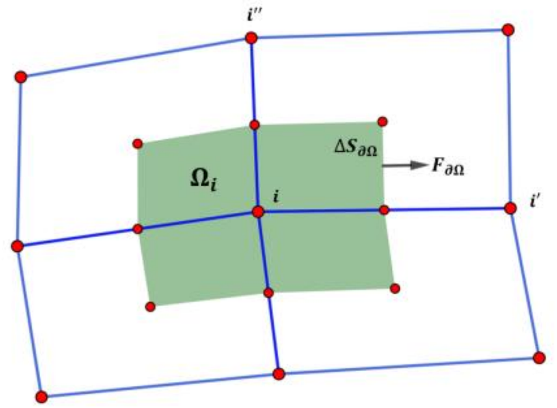
Reference: Airbus"Meet the Airbus Quantum Computing Challenge's five finalist teams" (https://www.airbus.com/en/newsroom/news/2020-10-meet-the-airbus-quantum-computing-challenges-five-finalist-teams)

Airbus: Optimization of aerodynamic characteristics in aircraft design [2020/11] 2/3

Problem setting as a quantum computer

- The finite volume method is used to approximately solve engineering problems that are mathematically **difficult to solve exactly** such as aerodynamic characterization of the airframe.
  - ✓ The finite volume method **divides the solution domain into a finite number of control volumes** and **replaces continuous partial differential equations with discontinuous linear algebraic equations**
  - ✓ However, **finer control volumes require more computing resources, making it difficult to perform calculations on a classical computer (supercomputer).**
- **Development of a quantum CFD solver that can quickly process input and output data of classical computers using quantum random access memory (QRAM [*1])**
  - ✓ This method, based on the finite volume method and quantum computers, optimizes the CFD time integration process in aircraft design and can exponentially accelerate the computation time.
- Since the Airbus competition is designed to explore development techniques using NISQ quantum computers, **it seems to be taking advantage of gated quantum computers.**

*1: QRAM is equivalent to RAM in a classical computer, and when given a memory address, it outputs a quantum state from the corresponding quantum bit string.



Control volume with solution area gridded

(F is the flux value at the interface used in the discretization equation, S is the area, and Ω is the volume.)

References: Airbus"Meet the Airbus Quantum Computing Challenge's five finalist teams" (https://www.airbus.com/en/newsroom/news/2020-10-meet-the-airbus-quantum-computing-challenges-five-finalist-teams), arXiv"Quantum Finite Volume Method for Computational Fluid Dynamics with Classical Input and Output" (https://show.originqc.com.cn/prod/website/ResumeDelivery/2102.03557.pdf), CYBERNET (https://www.cybernet.co.jp/ansys/learning/glossary/yuugentaisekihou/)

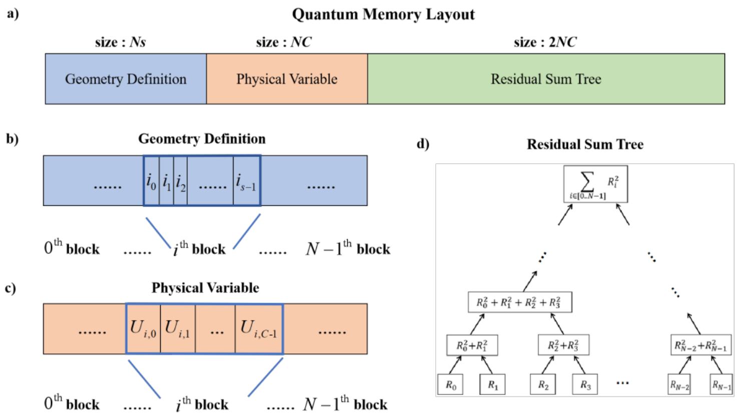
Airbus: Optimization of aerodynamic characteristics in aircraft design [2020/11] 3/3

Industry	Discrete Manufacturing
Process	R & D and product design
Method	Simulation

Expected business benefits

- **Each iteration step in the integration calculation is reduced from O (N) in classical computer to O (LogN), and the total calculation time by QCFD (CFD using quantum computer) is accelerated exponentially compared with classical computer.**
- **The quantum acceleration by QCFD is limited to the case where the problem size (N) is large enough.**
  - ✓ The conditions under which the fast performance of the QCFD algorithm is guaranteed depend on N and the computational accuracy (ε), and the conditions under which quantum acceleration is satisfied are N>>1/ε2.
- **We have created a large-scale computational fluid dynamics model for aerodynamic characterization of the fuselage shape, which is difficult to do with classical computers, and have increased the feasibility of using quantum computers to simulate energy-efficient fuselage designs.**
  - ✓ However, it is necessary to clarify the calculation accuracy and the convergence of calculation, which are the remaining issues of the above algorithm.

Airbus Airframe Design



Structure of QRAM (3 blocks)
Geometry Definition: preserving problem inputs
Physical Variable: keeps the physical variable of the discretized equation
Residual Sum Tree: Residual vector tree structure

Reference: Emerging Technology Review"Airbus uses quantum computers to design aircraft, NISQ starts developing quantum algorithms" (https://etechnologyreview.com/2019/11/08/%E3%82%A8%E3%82%A2%E3%83%90%E3%82%B9%E3%81%AF%E9%87%8F%E5%AD%90%E3%82%B3%E3%83%B3%E3%83%94%E3%83%A5%E3%83%BC%E3%82%BF%E3%81%A7%E8%88%AA%E7%A9%BA%E6%A9%9F%E3%82%92%E3%83%87%E3%82%B6%E3%82%A4%E3%83%B3/)

Rolls-Royce: Improving Jet Engine Performance【2023/05】1/2

Industry: Discrete Manufacturing
Process: R & D and product design
Method: Simulation

Background

- **We need to build state-of-the-art, high-efficiency jet engines** to achieve sustainable aircraft, but **jet engines are so complex that they are expensive to design and computationally expensive.**
- Rolls-Royce **plans to model jet engines in simulations that combine both classical and quantum computing** in jet engine design
- **Quantum computing research around the world is now powered by NVIDIA GPUs, and much of the world's quantum computing software now supports GPU acceleration using the NVIDIA quantum platform.**

Issues and motivation to be solved

- **Ensure a system to enjoy the benefits of quantum advantage when the era of quantum computers arrives**
- advance **the implementation of hardware-independent algorithms optimized for quantum computers of the future (faster than classical computers),** as well as today's quantum computers

Expected business benefits

- **10 million layers with 39 qubits** *1 **Design and simulation of the world's largest measurable quantum computer circuit for CFD**
- With GPUs, **we're preparing for a future with powerful quantum computers.**

*1: Current quantum computers can only handle a few layers (as of 2023/05), but run 10 million layers of circuits in a simulation

Example of a jet engine

Reference: NVIDIA"NVIDIA, Rolls-Royce and Classiq announce quantum computing breakthroughs for computational fluid dynamics in jet engines" (https://www.nvidia.com/ja-jp/about-nvidia/press-releases/2023/nvidia-rolls-royce-and-classiq-announce-quantum-computing-breakthrough-for-computational-fluid-dynamics-in-jet-engines/), PRTIMES"Rolls-Royce and Classiq team up to design quantum algorithms for fluid dynamics" (https://prtimes.jp/main/html/rd/p/000000007.000101286.html)

Rolls-Royce: Improving Jet Engine Performance【2023/05】2/2

Industry	Discrete Manufacturing
Process	R & D and product design
Method	Simulation

Problem setting as a quantum computer

- Implementation of **New Analysis Algorithms for Fluid Flow Analysis (CFD) *1)**
- Regarding the HHL algorithm *2 for solving linear equations, the nonlinear part is solved by a classical computer, and the linear part is solved by a quantum computer
- **Leverage Classiq's proprietary platform to** develop **state-of-the-art quantum circuits optimized for HHL algorithms**
- For the circuit synthesized above, **Simulate the circuit using the NVIDIA A100 Tensor Core GPU.**

Classiq's Quantum Software Development Support Platform

*1: CFD is a numerical analysis and simulation method that observes the flow by solving equations related to the motion of a fluid (Euler equations, Navier-Stokes equations, or their derivatives) on a computer using the numerical solution of partial differential equations, etc.

*2: Harrow-Hassidim-Lloyd (HHL) algorithm is a fast algorithm for solving simultaneous equations. Simultaneous linear equations are used in all kinds of scientific and technical calculations such as electromagnetic and thermohydrodynamic analysis and machine learning.

Reference: Classiq"Quantum software platform enabling design, optimization, analysis and execution of quantum algorithms"(https://ja.classiq.io/, https://prtimes.jp/main/html/rd/p/000000007.000101286.html)

Process Manufacturing

Simulation	Molecular Simulation for Application to Automotive Material Design	P65
	Modeling of Oxygen Reduction Reaction in Automotive Fuel Cell Development	P67
	Prediction of material properties and simulation of various chemical reactions	P68
	High-precision energy calculation for large-scale molecules and solids	P70
	Material property prediction using existing material data × machine learning	P72
	Improving the Design of Composite Materials for Aircraft	P74
	Accelerated platform for material design and reaction analysis	P75

TOYOTA: Molecular Simulation for Application to Automotive Material Design 【2023/01】1/2

Industry: Process Manufacturing
Process: research and development
Method: Simulation

Background

- **Large-scale computer simulations are becoming increasingly important in all aspects of automotive research and development, and the need for HPC (High Performance Computing) is growing.**
- As the Moore's Law factory of classical computing power is expected to die down, the promise of quantum computing is growing these days.
  - ✓ For example, while research and development related to functional materials is an essential element for achieving carbon neutrality, **research subjects related to all kinds of materials such as battery reactions** are known to be compatible with quantum computers.

Issues and motivation to be solved

- **Calculations of electronic states represented by the DFT method (density functional method)** are diversified in the research and development of automotive materials, and **quantum chemical calculations are used as a compass for material screening,** such as the design of electrode materials for lithium-ion batteries.
- Quantum computers are expected to improve prediction accuracy because they can treat **electron correlations (many-body interactions between electrons) more strictly** than existing DFT methods.
- In this verification, **TOYOTA and QunaSys collaborated to compare the actual thermodynamic behavior of liquid hydrogen in hydrogen storage for fuel cells and hydrogen engines with the existing DFT method and quantum computer in terms of the interaction between hydrogen molecules**

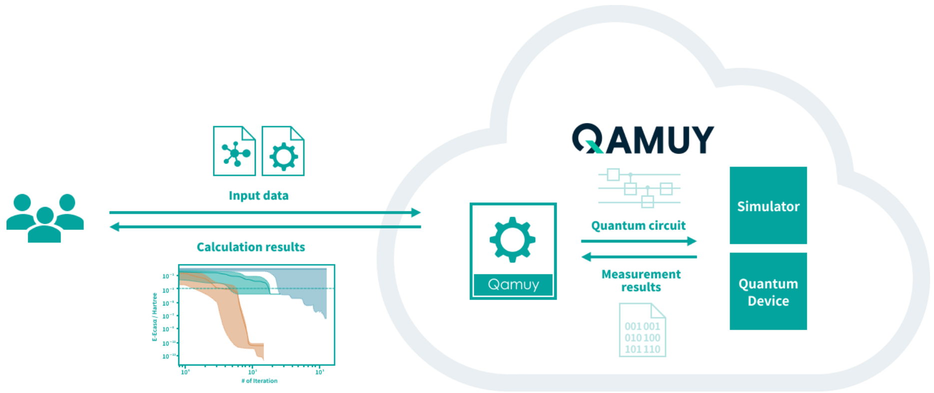
Reference: J-STAGE "Applicability of Quantum Computing to Automotive Materials Design" (https://www.jstage.jst.go.jp/article/jsaeronbun/54/1/54_20234032/_pdf/-char/ja)

TOYOTA: Molecular Simulation for Application to Automotive Material Design 【2023/01】2/2

Industry	Process Manufacturing
Process	research and development
Method	Simulation

Problem setting as a quantum computer

- **Van der Waals interaction between hydrogen molecules is taken up, and minute energy change between different hydrogen molecules is calculated** was performed as an object in which the effect of electron correlation may be conspicuous.
- As a calculation method of electronic state, **VQE utilizing quantum computer, * DFT method used in MI (material informatics) of method and classical computer** are mainly used.
- The electronic state calculation by the VQE method was performed using **QynaSys quantum chemical calculation cloud service Qamuy**.
  - ✓ **As a simulator of quantum computer (gate), Qulacs which can be implemented in Python base was used.**

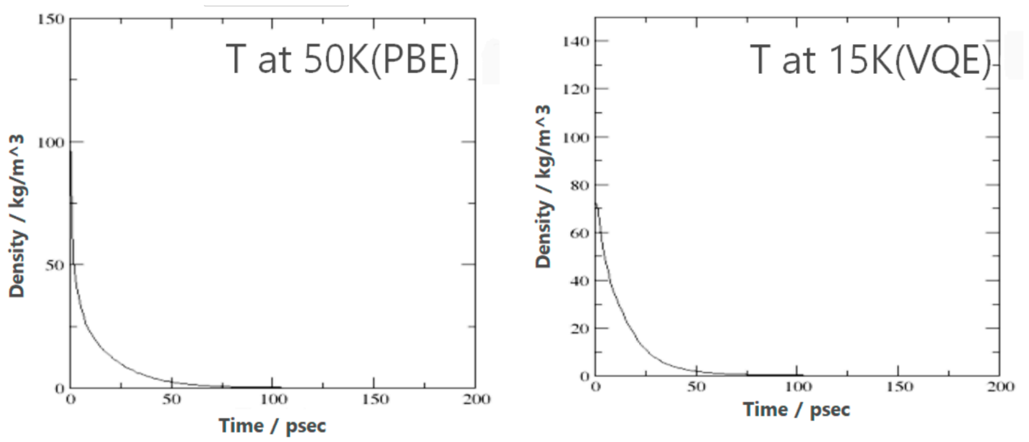


How to Use Qamuy

Reference: J-STAGE "Applicability of Quantum Computing to Automotive Material Design " (https://www.jstage.jst.go.jp/article/jsaeronbun/54/1/54_20234032/_pdf/-char/ja,), Qamuy" Flow image of using Qamuy " (https://qunasys.com/services/qamuy/) ", "How to use Qulacs, the world's fastest simulator " (https://dojo.qulacs.org/ja/latest/notebooks/3.1_Qulacs_tutorial.html)[LINK1]

Expected business benefits

- Molecular dynamics simulations of the evaporation process of liquid hydrogen (3810 atoms) were performed by the classical DFT method (PBE, * and) **and the quantum VQE method,** while gradually increasing the temperature, and the temperature at which liquid hydrogen drastically reduces its density was measured.
- **The results obtained by the quantum VQE method are closer to the experimental ones.**
  - ✓ The measured boiling point of liquid hydrogen is about 20 K (Kelvin). Evaporation is observed at about 15 K by the quantum VQE method, while the classical DFT method at 50 K. The measured boiling point of liquid hydrogen is about 20 K.



Comparison of Hydrogen Vaporization Behaviors by Classical DFT (PBE) and Quantum VQE

Reference: J-STAGE "Applicability of Quantum Computing to Automotive Materials Design" (https://www.jstage.jst.go.jp/article/jsaeronbun/54/1/54_20234032/_pdf/-char/ja)

BMW: Modeling of Oxygen Reduction Reaction in Automotive Fuel Cell Development【2022/12】

Industry: Process Manufacturing
Process: research and development
Method: Simulation

Background

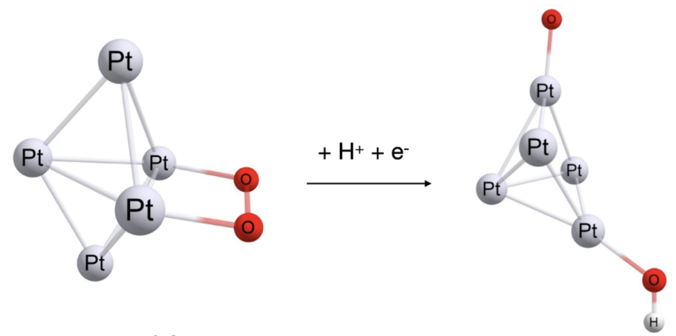
- The slowness of the oxygen reduction reaction (ORR) is an important issue **in the development of new fuel cell technologies for automobiles.**
- Most studies on atomic modeling of catalytic and electrocatalytic chemical reactions, such as ORR, use density functional theory (DFT), which is **limited in computational accuracy.**
- It is known that **DFT calculations fail** for systems in which strong (static) electronic correlations are involved, such as metal complexes (compounds in which metal and non-metal atoms are bonded) and transition states.

Issues and motivation to be solved

- By utilizing quantum computers, it is expected that **complex systems can be accurately calculated using first principles** without losing accuracy using approximate methods such as DFT.
- BMW has **demonstrated the ORR mechanism for the oxygen reduction reaction on platinum clusters.**

Problem setting as a quantum computer

- Targeting the oxygen reduction reaction on a platinum cluster, **using quantum computers to calculate the ground state energy** of the interaction between platinum cluster and oxygen
- This use case **leverages quantum simulations from Amazon Braket, AWS's quantum computing service, using InQuanto, Quantinuum's quantum computing science software platform**.
  - ✓ To perform quantum chemistry calculations, **assume that the gate method (simulation) is used**



Model of Oxygen Reduction Reaction on Platinum Clusters

Expected business benefits

- **We have constructed a minimal model of the reaction steps occurring on platinum clusters and performed an exploratory calculation of their ground state energies.**
- This use case was interesting to BMW because it **could be applied to vehicle fuel cell design in the future**.

Reference: AWS"Exploring computational chemistry using Quantinuum's InQuanto on AWS" (https://aws.amazon.com/jp/blogs/quantum-computing/exploring-computational-chemistry-using-quantinuums-inquanto-on-aws/)

TOPPAN The University of Osaka:
Prediction of material properties and simulation of various chemical reactions【2023/04】1/2

Industry — Process Manufacturing
Process — research and development
Method — Simulation

Background

- Quantum computers are expected to be a revolutionary technology that will revolutionize various industries.
  - ✓ In particular, **in the field of chemistry, the creation of innovative new materials is expected.**
- Materials development so far **requires a lot of time** because researchers design molecular structures that are expected to have desired physical properties based on past data and experience, and search for promising compounds by repeating synthesis and measurement of physical properties.
- In recent years, efforts have been made to **accelerate research and development by utilizing new methods such as materials informatics (MI).**
  - ✓ Computational chemistry to elucidate mechanisms of functional expression
  - ✓ Efficient screening of vast amounts of material data using AI and other technologies

Issues and motivation to be solved

- By using quantum computers for computational chemistry, there is a growing expectation that **there is a possibility of high-speed, high-precision calculations of complex molecules that cannot be calculated with classical computers.**
- Molecular structures and properties calculated by quantum computers are expected to become important learning data for MI, and to greatly expand the search area for screening.
- Toppan Printing and the The University of Osaka Research Center for Quantum Information and Quantum Life (QIQB) have started **joint research to develop and demonstrate quantum chemical calculation algorithms.**

Expected business benefits

- Through this joint research, we aim to **reform and speed up the process of material development and evaluation, and create innovative new materials and functional materials.**

Reference: TOPPAN Holdings Co., Ltd. "Toppan Printing and The University of Osaka Quantum Information and Quantum Life Research Center start joint research on materials development and evaluation methods using quantum computers." (https://www.holdings.toppan.com/ja/news/2023/04/newsrelease230411_1.html)

TOPPAN The University of Osaka: Prediction of material properties and simulation of various chemical reactions【2023/04】2/2

Problem setting as a quantum computer

- Development of a quantum chemical calculation algorithm **to calculate physical properties of new materials and perform analytical simulations of chemical reactions on a quantum computer**
  - ✓ Prediction of physical properties of materials developed and manufactured in Toppan's business area, such as semiconductors and display-related components, architectural materials, and packages
  - ✓ Operations such as analytical simulations of various chemical reactions
- These will **verify whether it is possible to calculate molecules that could not be calculated with classical computers.**
- use the **gate method** to perform quantum chemical calculations

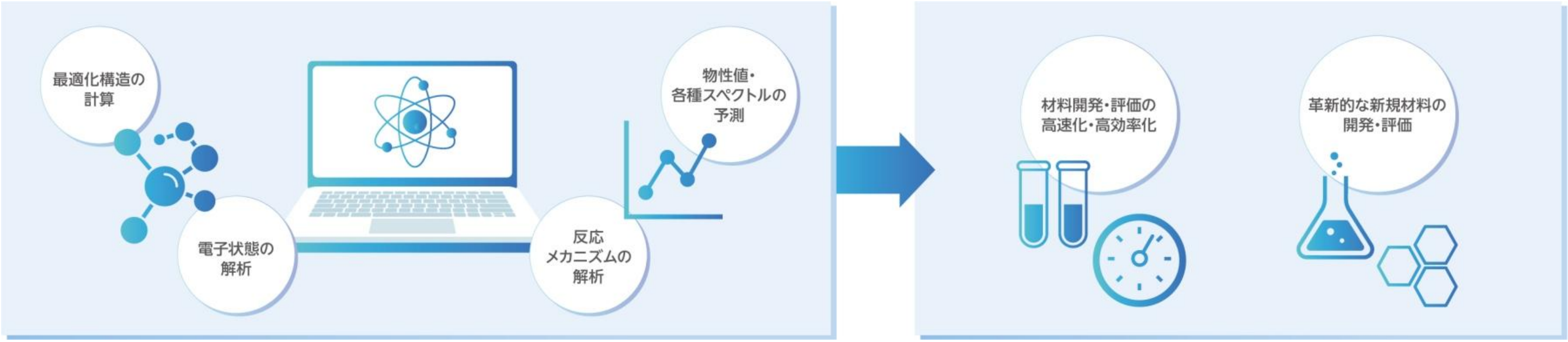


Image of quantum computer utilization

Reference: TOPPAN Holdings Co., Ltd. "Toppan Printing and The University of Osaka Quantum Information and Quantum Life Research Center start joint research on materials development and evaluation methods using quantum computers." (https://www.holdings.toppan.com/ja/news/2023/04/newsrelease230411_1.html)

Mitsubishi Chemical, Keio University, and IBM: High-precision energy calculation for large-scale molecules and solids【2024/06】1/2

Industry: Process Manufacturing
Process: research and development
Method: Simulation

Background

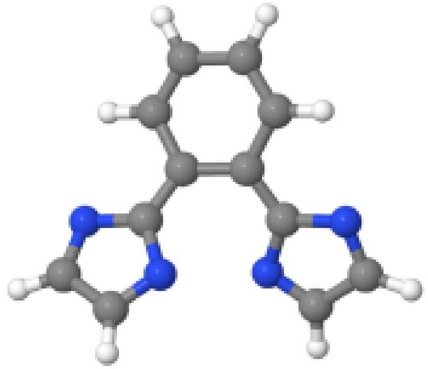
- Physical properties of molecules and solids can be determined by calculating the states of electrons contained in substances.
- However, since the calculation of the electronic state **increases exponentially with the number of electrons,** the current method is **approximated**
- **DFT (density functional), which approximates electron correlation,** is widely used to calculate the ground state of electrons, the lowest energy state, but **it is difficult to obtain sufficient accuracy for materials with complex electronic structures with strong Coulomb repulsion.**

Issues and motivation to be solved

- Quantum computers are expected to **improve the accuracy of electron ground state calculations in materials with complex electronic structures.**
- While current quantum computers are limited in the number of qubits and gates, Mitsubishi Chemical, Keio University and IBM worked together to **develop a calculation method for a large-scale, high-precision calculation that exceeds the performance of a single quantum computer**

Expected business benefits

- Combining the two developed calculation methods **HTN + QMC** and **pseudo-Hadamard test**, we calculated the photochromic model molecules monoallyldiimidazole, *1 and *** 1**. As a result, we were able to **calculate the ground state with high accuracy**
  - ✓ Concretely, it was calculated with an accuracy of 0.042±2.0 milli-Hartree *2, **higher than the accuracy for understanding general chemical phenomena (1.6 milli-Hartree)**



Structure of Monoallyldiimidazole Calculated in the Present Study
Gray represents carbon, white represents hydrogen, and blue represents nitrogen.

Reference: Keio Gijuku "Quantum Computer Technique for Large-Scale High-Precision Energy Calculations for Molecules and Solids Published in Nature Research" (https://www.keio.ac.jp/ja/press-releases/files/2024/6/10/240610-1.pdf)

*1: A compound consisting of one allyl group and two imidazoles. Imidazoles are used in a variety of applications, from pharmaceuticals to commodities.
*2: Atomic units used in quantum chemistry to deal with atomic and electron scales

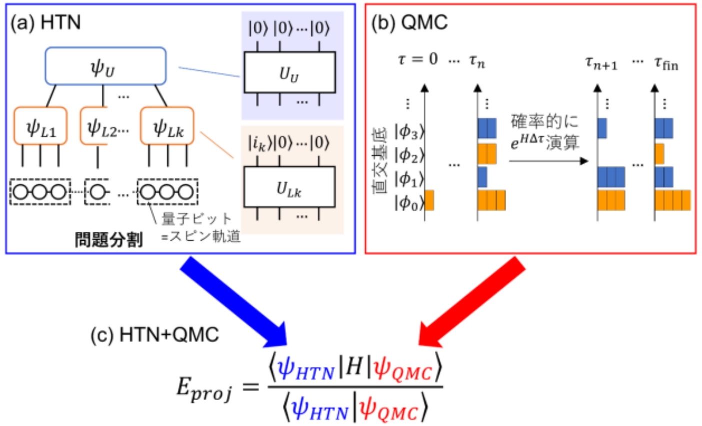
Mitsubishi Chemical, Keio University, and IBM:
High-precision energy calculation for large-scale molecules and solids【2024/06】2/2

Industry	Process Manufacturing
Process	research and development
Method	Simulation

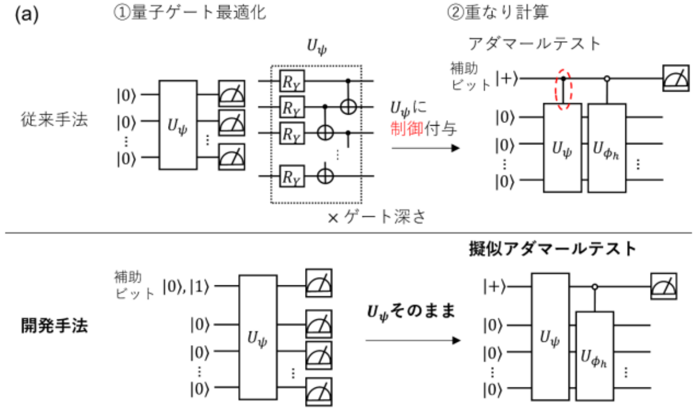
Problem setting as a quantum computer

- **Two calculation methods were** developed **to obtain the energy of large-scale molecules and solids with high accuracy.**
  - ✓ **HTN + QMC** is developed by combining the hybrid tensor network (HTN), which divides a quantum state larger than the size of a quantum computer into smaller tensors (blocks) using a quantum computer and a classical computer to connect the tensors, and the quantum Monte Carlo (QMC), a high-precision energy calculation method.
  - ✓ **Pseudo Hadamard Test** to Calculate Overlap Between Quantum States Effectively on a Quantum Circuit
- Using this calculation method, **photochromic model molecule,** * and **energy calculation of** were performed.
- The machine used was **IBM's gated commercial quantum computer, IBM Quantum System One.**

*: the property of the material to change color as the intensity of light changes;



HTN+QMC approach



simulated Hadamard test

Reference: Keio Gijuku "Quantum Computer Technique for Large-Scale High-Precision Energy Calculations for Molecules and Solids Published in Nature Research" (https://www.keio.ac.jp/ja/press-releases/files/2024/6/10/240610-1.pdf)

Sekisui Chemical and Hitachi:
Material property prediction using existing material data × machine learning【2022/12】1/2

Background

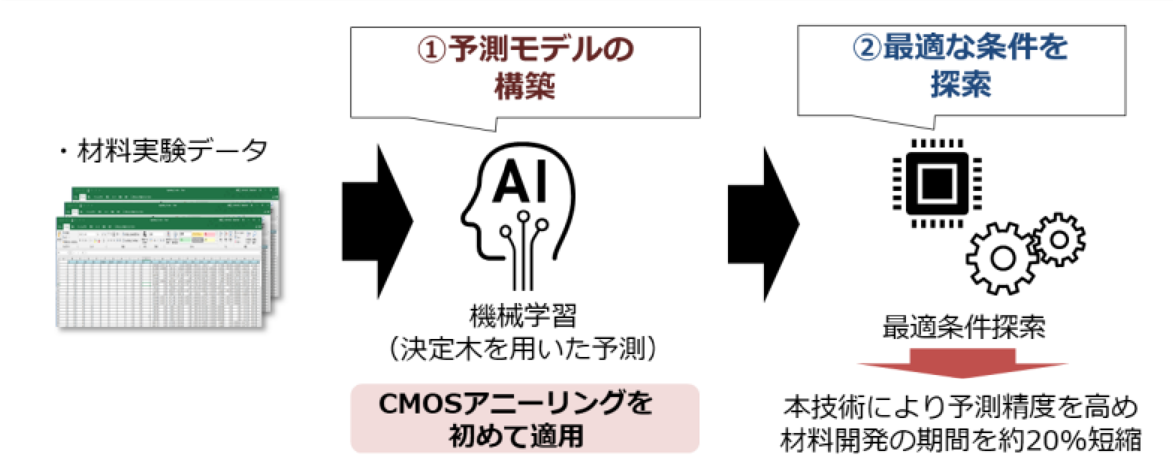
- Until now, material development has **depended on the experience and intuition of researchers, and took a long time and cost to commercialize**
- On the other hand, in the market, demands for material development are becoming more diverse and sophisticated due to shorter product life cycles and resource constraints, and **MI (Material Informatics) efforts are in full swing** to meet these demands.
- Hitachi has continued to develop technologies to realize a data management and analytics platform that uses data to streamline the material development process. **We have responded to the needs of customers in the materials industry by providing materials development solutions that apply MI.**

Issues and motivation to be solved

- In conventional materials development, various conditions related to material creation were selected based on the experience and intuition of researchers, and prediction models were constructed to predict the properties of materials. However, there was a **limitation in improving accuracy because the conditions were not examined comprehensively**
- In this demonstration, Sekisui Chemical and Hitachi jointly developed a new machine learning model to accelerate material development and verified the possibility of shortening the material development period.

Problem setting as a quantum computer

- **We have developed a new method to improve prediction accuracy** by using quantum technology and comprehensively considering the conditions involved in the creation of materials.
- The developed prediction accuracy model was **applied to the problem of predicting the properties of existing organic materials from their molecular structures, and the accuracy was compared with the conventional method**.
- The machine uses **CMOS annealing, Hitachi's pseudo quantum computer technology**



Conceptual diagram of the developed machine learning model

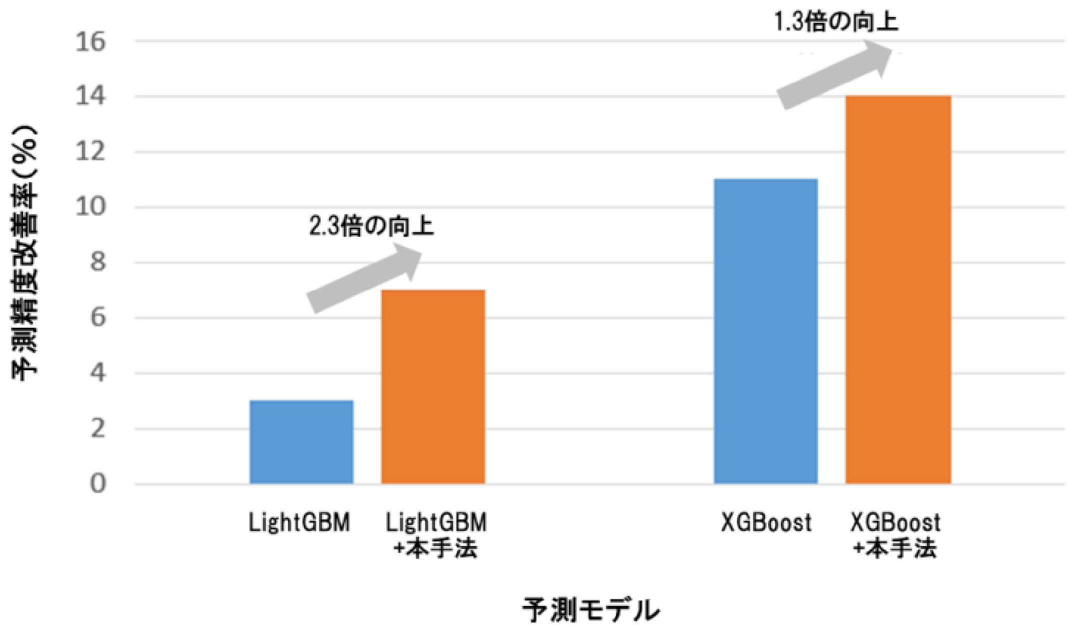
Reference: Hitachi, Ltd. "Demonstration that the use of pseudo quanta can further shorten the material development time by 20% using conventional MI" (https://www.hitachi.co.jp/New/cnews/month/2022/12/1216.pdf)

Sekisui Chemical and Hitachi: Material property prediction using existing material data × machine learning【2022/12】2/2

Industry	Process Manufacturing
Process	research and development
Method	Simulation

Expected business benefits

- In terms of prediction accuracy by machine learning, we compared the conventional machine learning algorithm (LightGBM, XGBoost) alone and the method applied to the conventional machine learning algorithm. As a result, we were able to **achieve better prediction accuracy than the conventional machine learning algorithm alone.**
- In the case of material development using this technology, **the time required for material development can be reduced by about 20%** compared with the conventional method using MI.



Results of improved prediction accuracy when applying the developed method to the conventional technology

Reference: Hitachi, Ltd. "Demonstration that the use of pseudo quanta can further shorten the material development time by 20% using conventional MI" (https://www.hitachi.co.jp/New/cnews/month/2022/12/1216.pdf)

Boeing/IBM:
Improving the Design of Composite Materials for Aircraft【2023/01】

Industry	Process Manufacturing
Process	research and development
Method	Simulation

Background

- Boeing's plants **produce much of the world's critical aerospace infrastructure,** including satellites, defense systems, spacecraft, and commercial jets
- Many of the projects **utilize ply composites to assemble wings, fuselages, and other aerospace components** that are light as a feather, durable, and layered.
- The design of ply composites is a very complex problem that is **beyond the capabilities of conventional supercomputers, so Boeing engineers solve very complex problems by breaking them into smaller problems, but at a cost.**

Issues and motivation to be solved

- Boeing's ply design problem **has to deal with up to 100,000 variables, which is way beyond the power of a traditional supercomputer.**
- Boeing and IBM have teamed up to **harness quantum technology to solve complex problems in ply composites**

Problem setting as a quantum computer

- Solved a **simplified ply design problem** that essentially narrows down Boeing's ply design problem to find how to best stack layers of materials
  - ✓ The simplified ply design problem involves **40 variables**
- Instead of encoding one variable in each qubit, they **encoded three variables in each qubit** to solve the quantum optimization

Expected business benefits

- Using this quantum optimization method, we were able to **achieve a dramatic improvement in Processing efficiency (about twice as much)** in comparison with conventional quantum optimization algorithms.
- With this achievement, we were able to **analyze a very large optimization problem at the core of product design and show that quantum computers can solve part of that optimization problem**.

IBM"Boeing seeks new ways to engineer strong, lightweight materials" (https://www.ibm.com/case-studies/boeing)

Mitsui: Accelerated platform for material design and reaction analysis [2025/8] 1/2

<u>Industry</u> Process Manufacturing
<u>Process</u> research and development
<u>Method</u> Simulation

Background

- **In the fields of drug discovery, materials, and chemistry, the link between computation and experiment, which requires molecular-level precision, has become important. On the other hand, the maturity of quantum computation technology, the shortage of human resources, and the introduction cost have become bottlenecks, and many companies remain at the evaluation and examination stage.**
- Materials development requires complex computational processes that link quantum mechanical microphenomena with macroscopic product performance, and requires an environment in which leading-edge computational chemistry, quantum computation, and AI are integrated.
- Mitsui integrates the strengths of Qsimulate's classical computing software and Quantinuum's quantum computing software, and starts providing "QIDO," a quantum-classical hybrid platform that can be easily used in the cloud.

Issues and motivation to be solved

- **By improving the precision of molecular design, we will promote the introduction of quantum computers in the fields of drug discovery, materials, and chemistry, which are expected to bring innovation to drug discovery and material development.**
- Enhance molecular simulations by seamlessly connecting highly practical classical and advanced quantum computations

Problem setting as a quantum computer

- High-precision chemical reaction analysis is performed with QSimulate's classical calculation software "QSP Reaction" and applied to Quantinuum's quantum calculation software "InQuanto" to make quantum calculation more efficient

Reference: Mitsui & Co., Ltd.: "Launch of "QIDO," a quantum/classical hybrid platform aimed at accelerating drug discovery and material development" (https://www.mitsui.com/jp/ja/topics/2025/1251846_14877.html)

Mitsui: Accelerated platform for material design and reaction analysis【2025/8】2/2

Industry	Process Manufacturing
Process	research and development
Method	Simulation

Expected business benefits

- By utilizing the cloud environment, QIDO will be able to provide an environment that enables rapid and flexible experimental analysis of various research themes, and will promote the spread of quantum chemical technology, which previously required specialized knowledge, to more research sites.
- The user interface and automated analysis allow researchers to select the most appropriate method and conduct research efficiently.
  - Companies and research institutions can efficiently implement quantum technologies and contribute to accelerating their adoption
- **Use cases such as drug discovery, catalyst and enzyme design, sustainable materials, and energy technology are envisaged, including the search for chemical reaction pathways and excited state calculations. In the future, we plan to expand the functions specialized in each field sequentially with a view to application to battery technology and biotechnology.**

Conceptual image of QIDO

Reference: Mitsui & Co., Ltd.: "Launch of "QIDO," a quantum/classical hybrid platform aimed at accelerating drug discovery and material development" (https://www.mitsui.com/jp/ja/topics/2025/1251846_14877.html)

Drug Discovery and Healthcare

Combinatorial Optimization	Prediction of Allosteric Regulation of Proteins Expansion of drug discovery target	P78
	Search for mid-molecule drug candidates	P80
AI	Proof of Concept of Quantum AI Drug Discovery Process	P82
	Development of anticancer drug candidates using quantum AI	P84
	Genome analysis technology using quantum AI	P86
Simulation	Molecular simulations of the electronic structure of drug-metabolizing enzymes	P88
	Lead compound against Alzheimer's disease-causing enzyme BASE1	P91

Revorf Toshiba Digital Solutions: Prediction of Allosteric Regulation of Proteins Expansion of drug discovery target【2022/06】1/2

Industry: Drug Discovery and Healthcare
Process: research and development
Method: combinatorial optimization

Background

- In the drug discovery process, **drug discovery target**, *1 and **exhaustion of drug discovery target** are issues.
- On the other hand, a drug discovery method focusing on allosteric control *2 (allosteric drug discovery) can find proteins that have been considered difficult to discover as drug discovery target candidates, and is expected to **solve the drug discovery problem of target depletion.**
- In order to discover the allosteric control site *3 in a protein, **in vitro experiments,** *4 and **computational alternative techniques** are required, which require a great deal of labor and time.

Issues and motivation to be solved

- **Quantum technology is expected to be used** to replace predictions of allosteric regulation of proteins with calculations rather than experiments
- In this verification, Revorf and Toshiba Digital Solutions jointly **developed a new technology to solve allosteric control prediction as a combinatorial optimization problem,** and **attempted to predict allosteric control sites by calculation,** which could not be specified by conventional calculation methods.

Expected business benefits

- By using this method utilizing quantum technology, **we succeeded in computationally predicting allosteric control sites that could not be identified by conventional methods**
  - ✓ Comparison of allosteric regulatory sites calculated and predicted by quantum technology with known allosteric regulatory sites for multiple proteins, including KRAS, an oncogene.
- This verification increased **the possibility of discovering allosteric control sites by calculation alone and accelerating the search for drug discovery candidate compounds**

*1: A protein that is assumed to be responsible for a disease and is targeted in the design of a drug.
*2: Mechanisms that specifically regulate the conformation and activity of proteins that provide functional diversity
*3: Regions of the protein other than the active center where regulatory molecules (allosteric factors) bind
*4: An experiment in which an environment that mimics in vivo is created artificially in a test tube or incubator.

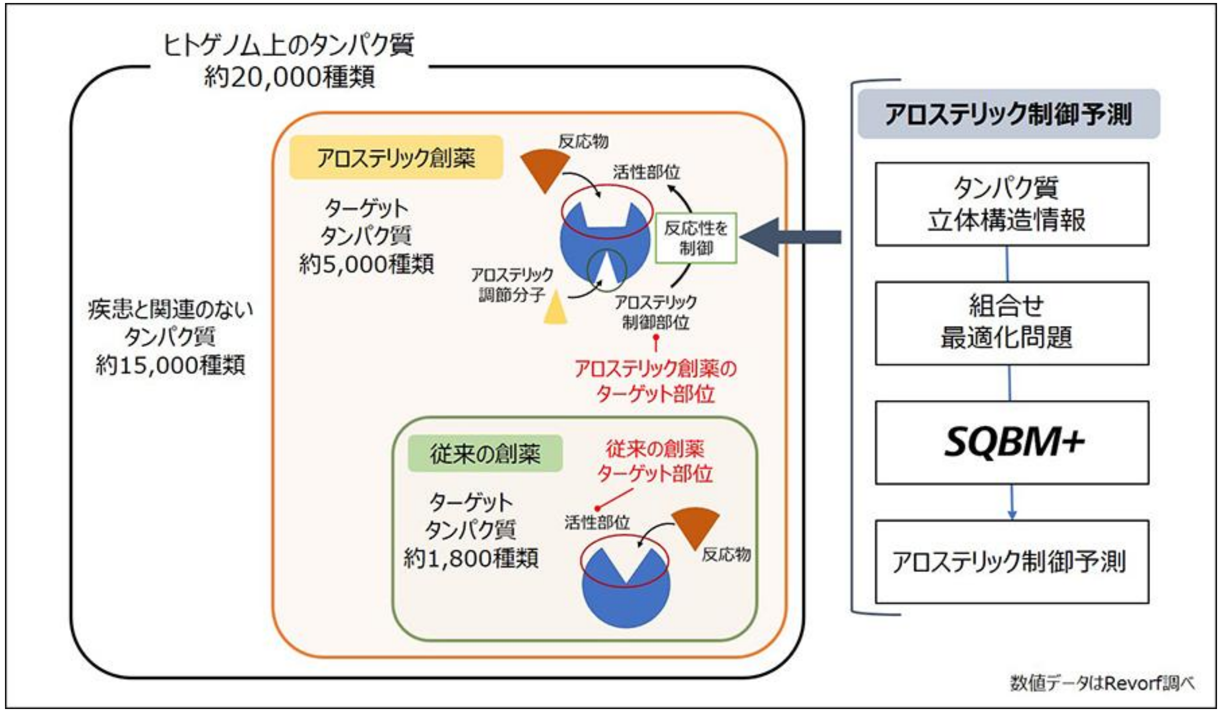
Reference: Toshiba Digital Solutions Corporation "Utilizing SQBM+TM, a quantum-inspired optimization solution, to verify technology applied to computational drug discovery" (https://www.global.toshiba/jp/company/digitalsolution/news/2022/0627.html)

Revorf Toshiba Digital Solutions: Prediction of Allosteric Regulation of Proteins Expansion of drug discovery target【2022/06】2/2

Industry	Drug Discovery and Healthcare
Process	research and development
Method	combinatorial optimization

Problem setting as a quantum computer

- In this verification, **the allosteric control mechanism of protein is formulated as a combinatorial optimization problem, and the allosteric control is predicted by calculation** based on the three-dimensional structure information of protein.
- The machine utilizes **SQBM +, Toshiba's quantum-inspired optimization solution**.



Reference: Toshiba Digital Solutions Corporation "Utilizing SQBM+TM, a quantum-inspired optimization solution, to verify technology applied to computational drug discovery" (https://www.global.toshiba/jp/company/digitalsolution/news/2022/0627.html)

Peptidream Fujitsu: Search for mid-molecule drug candidates [2020/10] 1/2

Industry	Drug Discovery and Healthcare
Process	research and development
Method	combinatorial optimization

Background

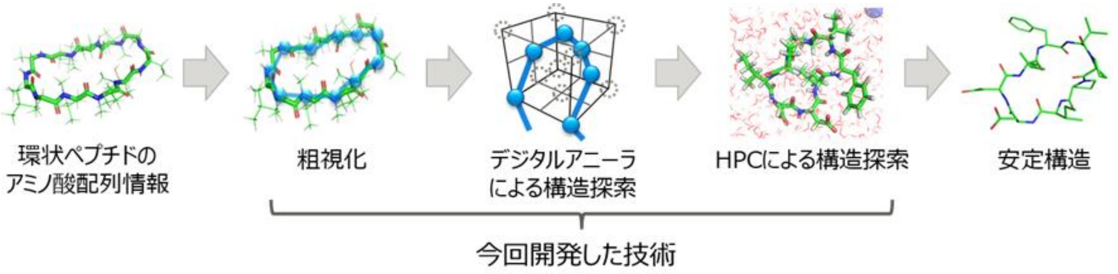
- PeptiDream is **developing a number of mid-molecule drug candidates.**
  - ✓ Medium-Molecule drugs are attracting attention because their molecular weight is between that of small-molecule drugs and antibody drugs (macromolecules), and because they combine the advantages of relatively low cost and low side effects.
- In the development of drug candidate compounds, **in the process of narrowing down candidate compounds from a library of several trillion compounds, it is difficult to search stable structures with conventional computers, and development takes a considerable amount of time.**

Issues and motivation to be solved

- Because **it is difficult to search for stable structures with classical computers and wet experiments must be repeated,** medium-molecule candidates **typically take months to years.**
- To solve this problem, Fujitsu and PeptiDream have started a joint research project to **develop a new basic technology to search the stable structure of medium-sized cyclic peptides as candidate compounds for drug discovery at high speed and with high accuracy** by utilizing quantum technology.

Problem setting as a quantum computer

- **Quantum and classical computer techniques were applied to search for stable structures of medium-sized cyclic peptides.**
  - ✓ Development of **Technology to Search for Stable Structures of Medium Molecules Using Coarse-Grained Structures** to Calculate Complex Molecular Structures Fast and Efficient Using Quantum Technology
  - ✓ **Development of technology to automatically convert coarse-grained models of candidate compounds obtained by quantum technology into all-atom models (models representing molecular structures using all atomic coordinates)**
- We use **Fujitsu digital annealer** as a quantum computer technology.



Flow of Search for Stable Structures of Medium-Sized Cyclic Peptides

Reference: Fujitsu Limited "Fujitsu and PeptiDream Search for Medium-Molecule Drug Candidates Fast, Accurately" (https://pr.fujitsu.com/jp/news/2020/10/13.html)

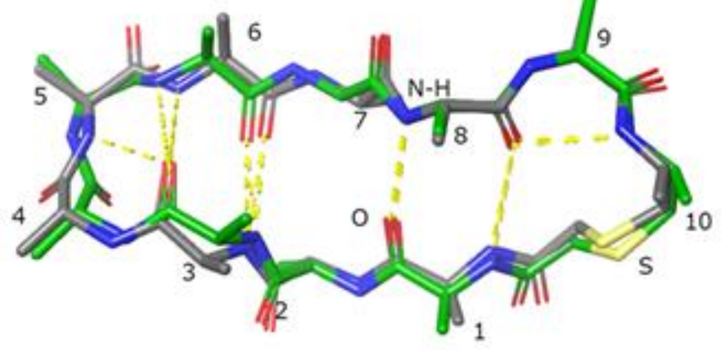
Peptidream Fujitsu: Search for mid-molecule drug candidates [2020/10] 2/2

Industry	Drug Discovery and Healthcare
Process	research and development
Method	combinatorial optimization

Expected business benefits

- **Using the newly developed technology, we succeeded in performing a high-speed search for the stable structure of a medium-sized cyclic peptide with high accuracy within 12 hours,** which was considered difficult to obtain by conventional classical computer calculations
- Comparing the structures calculated by the newly developed technology with those derived from actual experiments, **the possibility of searching for candidate compounds that are almost the same as those in actual experiments with high precision and minimizing the experimental steps required to search for candidate compounds** has been raised.
  - ✓ The deviation of the main chain * is 0.73 angstroms (1 angstrom =0.1 nanometers), which is as accurate as the experiment.
- By shortening the research period and the experimental period, it is possible to use the remaining time to develop new drugs.

*: Molecular chains that form the backbone of the structure of a polymer compound.



Comparison of experimental and computational structures
(Only the main chain is shown; gray is the experimental structure; green is the calculated structure.)

Reference: Fujitsu Limited "Fujitsu and PeptiDream Search for Medium-Molecule Drug Candidates Fast, Accurately" (https://pr.fujitsu.com/jp/news/2020/10/13.html)

JT: Proof of Concept of Quantum AI Drug Discovery Process【2024/10】1/2

Industry: Drug Discovery and Healthcare
Process: research and development
Method: AI

Background

- Generative AI has rapidly spread due to the large amount of data that can be learned on the Web. On the other hand, **human data is necessary for drug discovery, and the need to generate massive amounts of data to train AI is a barrier to development.**
  - ✓ Build drug discovery AI by running simulations and letting AI learn the data obtained
- **JT (Japan Tobacco Inc.) is currently focusing on the compound creation process,** but AI technology **has the potential to bring about innovative changes in all drug discovery processes, including translational research.**
- As it advances AI drug discovery, JT is **focusing on the innovation of quantum computers, both in terms of speed and the quality of the data they produce.**
  - ✓ **Strategic Partnership for Small Molecule Drug Discovery** with Qsimulate, a world leader in quantum simulation technology
- JT and D-Wave jointly announced **this initiative aimed at the development of innovative drug discovery technologies using AI and quantum computers**

Issues and motivation to be solved

- **Pharmaceutical companies need to remain competitive while dealing with the challenges of difficulty, uncertainty, and time in drug development**
- **Accelerate the process of discovering first-in-class small molecules** and create **quality improvements in various processes of drug discovery**

Problem setting as a quantum computer

- JT is currently in the implementation stage of developing its own advanced AI drug discovery technology. **Especially, the technology development in which physical simulation based on the basic principle and AI are interlocked and synchronized organically and closely is emphasized.**
- This initiative aims to **expand the development and application of AI for drug discovery in terms of speed, quality, and scope** by utilizing **D-Wave annealing type quantum computer** with JT's original AI technology

Reference: D-WAVE"Japan Tobacco and D-Wave announce joint project to develop innovative drug discovery technology using AI and quantum computers" (https://dwavejapan.com/%E6%97%A5%E6%9C%AC%E3%81%9F%E3%81%B0%E3%81%93%E7%94%A3%E6%A5%AD%E3%81%A8-d-wave%E3%80%81ai%E3%81%A8%E9%87%8F%E5%AD%90%E3%82%B3%E3%83%B3%E3%83%94%E3%83%A5%E3%83%BC%E3%82%BF%E3%82%92%E6%B4%BB%E7%94%A8/)

JT: Proof of Concept of Quantum AI Drug Discovery Process【2024/10】2/2

<u>Industry</u> Drug Discovery and Healthcare
<u>Process</u> research and development
<u>Method</u> AI

Expected business benefits

- Using quantum AI, **we aim to establish new advanced technologies to expand the quality and horizon of the search space for small molecules**.
- After the proof-of-concept project, JT's pharmaceutical division plans to **advance the creation of 'quantum AI drug discovery' technology and move to the stage where quantum computers can be used to design real molecules.**

Reference: D-WAVE"Japan Tobacco and D-Wave announce joint project to develop innovative drug discovery technology using AI and quantum computers" (https://dwavejapan.com/%E6%97%A5%E6%9C%AC%E3%81%9F%E3%81%B0%E3%81%93%E7%94%A3%E6%A5%AD%E3%81%A8-d-wave%E3%80%81ai%E3%81%A8%E9%87%8F%E5%AD%90%E3%82%B3%E3%83%B3%E3%83%94%E3%83%A5%E3%83%BC%E3%82%BF%E3%82%92%E6%B4%BB%E7%94%A8/)

Zapata AI: Development of anticancer drug candidates using quantum AI【2024/2】1/2

Industry	Drug Discovery and Healthcare
Process	research and development
Method	AI

Background

- Zapata AI started out as a quantum algorithm development software company as a spinout of Harvard, **before moving to focus on generative AI.**
  - ✓ Collaborates with quantum processor provider IonQ to **forge strategic partnership on quantum-generated AI technologies**
  - ✓ However, Zapata AI has since gone bankrupt (October 12, 2024).
- Zapata AI is working on industry-specific generative AI, trying to **apply quantum-generated AI to time-consuming and costly pharmaceutical research and development**

Issues and motivation to be solved

- **Drug R & D takes time and money**
- **demonstrate that quantum-generated AI effectively solves real-world problems**

Expected business benefits

- Quantum GANs using VQC **successfully produced molecules with physicochemical properties and performance that outperformed previous benchmarks**
- In addition, the small number of parameters **allowed us to observe quantum superiority in expressivity.**
- This study showed **the practical possibility of supporting drug discovery by quantum computer**.

Reference: QKAI"Zapata AI (ZPTA) goes public on NASDAQ. Completed management integration with Andretti Acquisition Corporation as a generative AI company that pivoted from the quantum field. Trading begins on April 1, 2024" (https://www.qcrjp.com/post/zapata-ai-zpta-nasdaq-go-public), QKAI “Interpretation of the Bankruptcy of Zapata AI in Japanese Market and Its Impact ” (https://www.qcrjp.com/post/zapata-ai-form8k?utm_source=twitter&utm_medium=blog.post-promoter&utm_campaign=efa0e2ed-a78a-4f84-aa0a-ac0e2b9dae5c), ACS"Exploring the Advantages of Quantum Generative Adversarial Networks in Generative Chemistry" (https://pubs.acs.org/doi/full/10.1021/acs.jcim.3c00562)

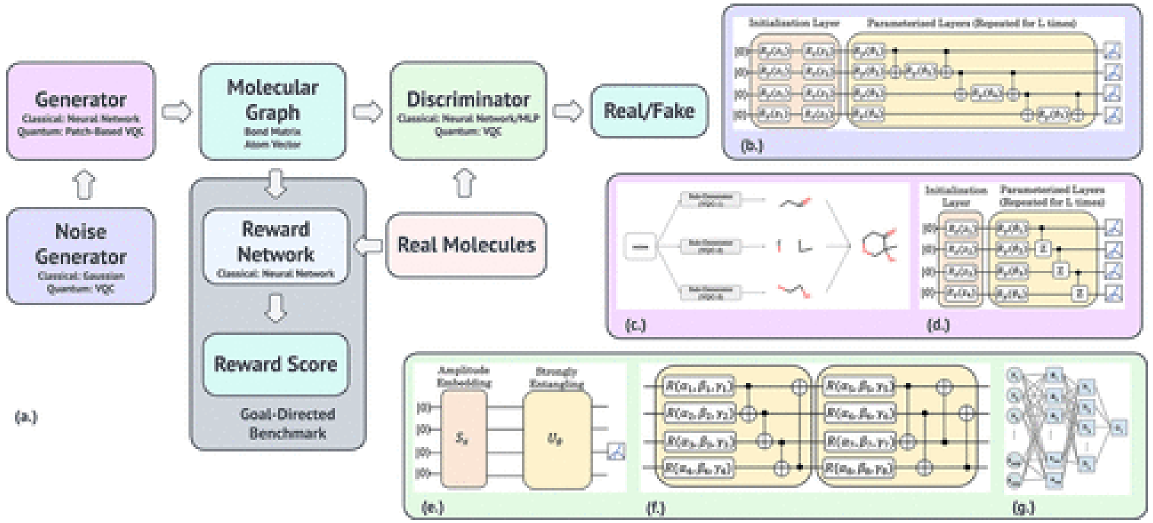
Zapata AI: Development of anticancer drug candidates using quantum AI【2024/2】2/2

Problem setting as a quantum computer

- Utilizing the Quantum-Classical Hybrid GAN *1 for the Discovery of Low-Molecule Compounds
- **Replaced each element of GAN with variational quantum circuits (VQC)**, *2 and demonstrated the advantages of quantum in drug discovery
- This project utilizes a 16 qubit IBM quantum computer

*1: A GAN is a network that alternately competes with a Discriminator and a Generator to generate real data.

*2: VQC refers to quantum circuits that implement quantum-classical hybrid computing



Overview of this initiative

Reference: ACS"Exploring the Advantages of Quantum Generative Adversarial Networks in Generative Chemistry" (https://pubs.acs.org/doi/full/10.1021/acs.jcim.3c00562)

BlueMeme, Kyushu University: Genome analysis technology using quantum AI【2025/12】1/2

Industry	Drug Discovery and Healthcare
Process	research and development
Method	AI

Background

- Transcription factors, which control the function of genes, are essential molecules for understanding life phenomena, disease research, and drug discovery.
- For many transcription factors, sufficient experimental data cannot be obtained, and high-precision analysis is difficult with conventional AI (deep learning). The decrease in prediction accuracy due to this "data shortage" is considered to be one of the factors hindering the progress of drug discovery and personalized medicine.
- BlueMeme and Kyushu University jointly develop QTFPred, a quantum AI model, as a new analysis method that uses quantum machine learning, a fusion of the principles of quantum computation and AI, to enable high-precision gene regulation prediction even with a small amount of data.

Issues and motivation to be solved

- For many transcription factors, the lack of experimental data makes it difficult to perform high-precision analysis with conventional AI.
- By utilizing quantum AI, we will attempt to improve the prediction accuracy, which hinders the progress of drug discovery and individual improvement, by predicting transcription factor binding patterns with high accuracy in a data-deficient environment.

Problem setting as a quantum computer

- QTFPred, a unique AI model equipped with a quantum computing mechanism, is designed to predict binding patterns with high accuracy even for transcription factors for which experimental data are limited.
- In tests using public human cell data, QTFPred achieved higher prediction accuracy than existing AI models on almost all tasks. Stable prediction performance was possible even under the condition of small amount of training data, and the performance was enough to be used in the research field.

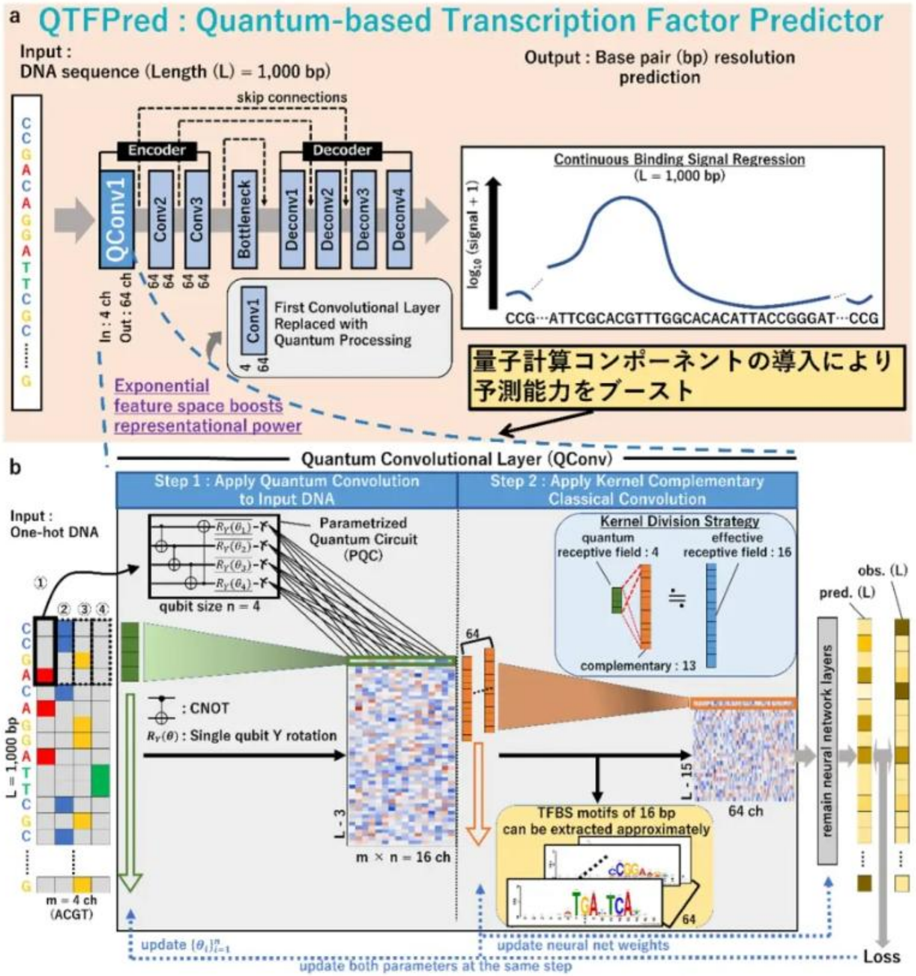
Reference: BlueMeme Co., Ltd.: "BlueMeme and Kyushu University announce QTFPred, a quantum machine learning model that opens up new possibilities for drug discovery and medical research" (https://www.bluememe.jp/news/pressrelease/2025-12-02/), Kyushu University "BlueMeme, Kyushu University publish quantum AI genome analysis results in international journal" (https://www.kyushu-u.ac.jp/f/64123/25_1202_03.pdf)

BlueMeme, Kyushu University: Genome analysis technology using quantum AI [2025/12] 2/2

Industry	Drug Discovery and Healthcare
Process	research and development
Method	AI

Expected business benefits

- **Development of a new AI model that can accurately predict even small amounts of data: QTFPred, a unique AI model equipped with a quantum computing mechanism, was developed. Designed to predict binding patterns with high accuracy even for transcription factors with limited experimental data**
- Demonstrated higher accuracy than conventional AI: QTFPred achieved higher prediction accuracy than existing AI models on almost all tasks tested using public human cell data. Stable prediction performance was possible even under the condition of small amount of training data, and the performance was enough to be used in the research field.
- Discovering patterns of cooperative binding of transcription factors: Analysis reveals how multiple transcription factors bind in concert. These results further deepen our understanding of life phenomena and offer new possibilities for drug discovery research.
- In the future, we will promote R & D in such directions as expansion of application **areas** (application to chromatin analysis (ATAC-seq) and disease-related genomic regions)**, verification with real quantum computers (development to large-scale analysis in the future), and development to drug discovery and personalized medicine** (application to disease risk prediction and target molecule search).



Overview of QTEPred

Reference: BlueMeme Co., Ltd.: "BlueMeme and Kyushu University announce QTFPred, a quantum machine learning model that opens up new possibilities for drug discovery and medical research" (https://www.bluememe.jp/news/pressrelease/2025-12-02/)

Boehringer Ingelheim:
Molecular simulations of the electronic structure of drug-metabolizing enzymes.【2022/09】1/3

Industry: Drug Discovery and Healthcare
Process: research and development
Method: Simulation

Background

- The development of innovative new drugs for diseases with significant unmet medical needs is a process requiring huge budgets and a time span of ~10 years, in which **molecular simulations are required in the R & D phase to understand the molecular states (electronic states in molecules) of molecules related to disease mechanisms (targets) and compounds that are effective against targets (leads).**
- Identification of energetically stable structures and molecular states through high-precision simulations of materials with complex molecular structures will facilitate accurate understanding of target molecules and compounds and accelerate the drug development process.

Issues and motivation to be solved

- On the other hand, **when a classical computer such as a supercomputer is used, if the accuracy of the simulation is increased (the number of electrons in a molecule = the number of orbitals), the calculation time becomes enormous,** and **the accuracy is lowered so that the calculation can be made in a realistic time.**
  - ✓ In classical calculations, increasing the number of orbits increases the computational complexity exponentially and requires more computational resources to obtain accurate results.
- Therefore, against the potential of molecular simulation, due to the increase in necessary computer resources, **utilization of molecular simulation for understanding molecular states is limited** such as target molecules at the stage of drug discovery.
- **Boehringer Ingelheim worked with Google to** estimate **the machine resources needed for molecular simulations to understand the electronic structure of CYP (cytochrome P450), a drug-metabolizing enzyme involved in the breakdown of drugs into the body.**
  - ✓ **CYP (cytochrome P 450)** is a biologically important enzyme, **a drug-metabolizing enzyme that plays an important role in drug metabolism and detoxification,** and the chemical intermediates involved in the catalytic cycle of CYP **have very complex electronic structures.**

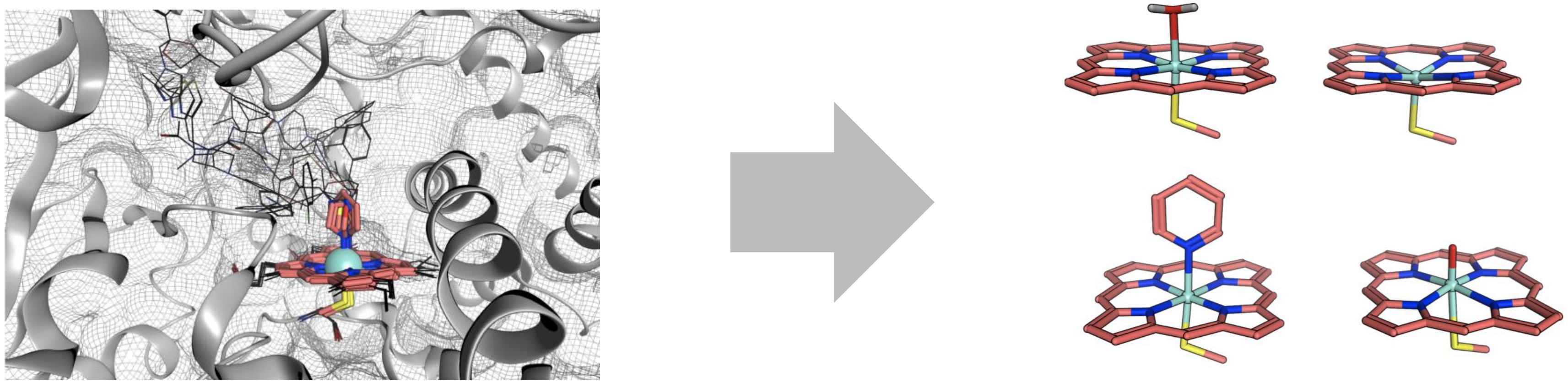
Reference: GeneQuest "What is CYP (drug-metabolizing enzyme) " (https://www.pnas.org/doi/full/10.1073/pnas. 2203533119) and" What is CYP (drug-metabolizing enzyme) " (https://genequest.jp/glossary/cyp#:~:text=CYP%E3%81%A8%E3%81%AF%E3%80%81%E3%82%B7%E3%83%88%E3%82%AF%E3%83%AD%E3%83%A0P450,%E3%81%99%E3%82%8B%E3%81%A8%E8%A8%80%E3%82%8F%E3%82%8C%E3%81%A6%E3%81%84%E3%81%BE%E3%81%99%E3%80%82)

Problem setting as a quantum computer

- **This demonstration is expected to be used in the lead search phase of drug discovery and medical research and development.** * Toward **understanding the electronic structure of CYP (cytochrome P 450), we estimated the resources required for molecular simulations using a CPU-based classical computer and a quantum computer.**

  *Since CYP is a drug-metabolizing enzyme involved in the breakdown of drugs that enter the body, it is assumed that CYP is not a target molecule that causes disease but a lead that exerts an effect on the target.

- For classical computers, simulation by density matrix renormalization group is assumed, and **for quantum computers, simulation using FTQC and quantum phase estimation (QPE) algorithm** is assumed.



Cytochrome P450 enzymes to be calculated
Proteins which are intrinsically complex electronic structures (left), and simple model systems (right) for quantum computer calculations.

Reference: PNAS "Reliably assessing the electronic structure of cytochrome P450 on today's classical computers and tomorrow's quantum computer"(https://www.pnas.org/doi/full/10.1073/pnas. 2203533119)

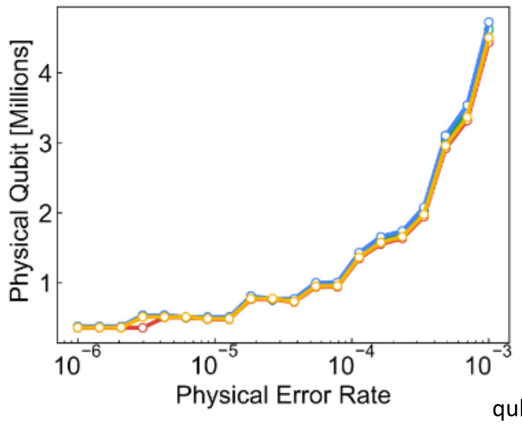
Boehringer Ingelheim: Molecular simulations of the electronic structure of drug-metabolizing enzymes.【2022/09】3/3

Industry	Drug Discovery and Healthcare
Process	research and development
Method	Simulation

Expected business benefits

- **Molecular simulation using a classical computer requires several years of computation time for the largest model (58 orbitals) and high accuracy (M=3000).**
  - ✓ M in the right table is an approximate parameter in quantum chemical calculation, and the larger the parameter, the higher the accuracy, but the higher the calculation load.
- The quantum computer **predicts that the largest model of an enzyme (cytochrome P450) can be simulated with THC in less than 100 hours of quantum computing time.**
  - ✓ THC is a tensor factorization scheme that affects resource estimation in quantum computers and is the least computationally expensive.
  - ✓ **FTQC, assuming a realistic error rate (0.1%), would require approximately 5 million physical qubits**

Number of physical qubits (1 million)

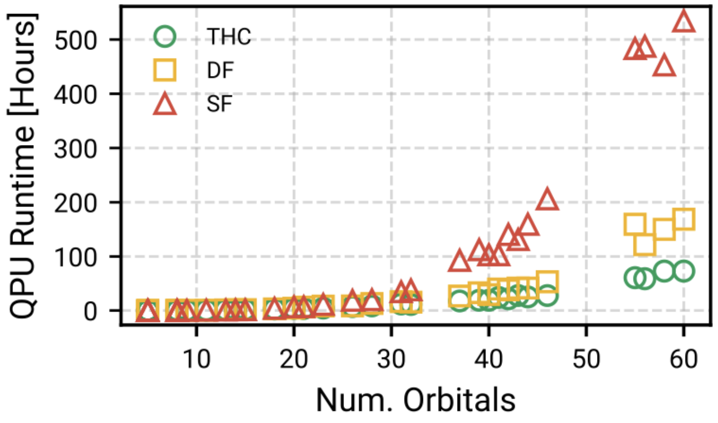


qubit error rate

Physical qubit requirements for computation

	G ($M = 1500$)	X ($M = 1500$)	X ($M = 3000$)
CPU time (hrs)	1800	4570	36564
Memory (Gb)	48	87	348
Disk (Gb)	235	572	2288

Estimated resources required for computation on classical computers
(G: 43 orbitals, X: 58 orbitals)



*Quantum bit error rate is assumed to be 0.1%

*Markers are results at specific value settings

Estimated resources needed for computation on a quantum computer

- SF: Single factorization is a basic method of decomposing a tensor into a single factor.
- DF: Double factorization is a method of decomposing a tensor into two factors.IT decomposes tensors more efficiently than single factorization and reduces computational costs.
- THC: The tensor hypershrinkage scheme is method that reduces the computational cost most and is an advanced decomposition method that shrinks tensors in multiple dimensions.

Reference: PNAS "Reliably assessing the electronic structure of cytochrome P450 on today's classical computers and tomorrow's quantum computer"(https://www.pnas.org/doi/full/10.1073/pnas. 2203533119)

Roche, Quantinuum: Lead compound against Alzheimer's disease-causing enzyme BASE1 【2021/10】1/2

Industry	Drug Discovery and Healthcare
Process	research and development
Method	Simulation

Background

- Simulating complex and strongly correlated chemical systems is widely believed to be one of the areas that will benefit most from advances in quantum computing because standard methods are inaccurate or expensive.
  - ✓ In fact, over the past half century, there has been an explosion of research on quantum algorithms for materials simulation, and research has been conducted in a variety of fields
- The synthesis of new drug candidates requires considerable medicinal chemistry effort. The need for synthesis can be limited by **screening candidate molecules using a variety of approaches to prioritize the most promising compounds in CADD (computer-aided drug design).**
  - ✓ At CADD, **quantum technology is expected to be utilized.**

Issues and motivation to be solved

- Development of low-scaling quantum mechanical methods that can simulate proteins using DFT (density functional) and CC (coupling cluster) approaches is underway, but there is a need for **accurate Methods for large-scale simulations.**
- **A team of Roche and Quantinuum (formerly Cambridge Quantum Computing) worked on protein-ligand binding energy calculations using a real quantum computer,** the team said.

Reference: arXiv"Quantum Computational Quantification of Protein-Ligand Interactions" (https://arxiv.org/pdf/2110.08163)

Roche, Quantinuum: Lead compound against Alzheimer's disease-causing enzyme BASE1 【2021/10】2/2

Industry: Drug Discovery and Healthcare
Process: research and development
Method: Simulation

Problem setting as a quantum computer

- We used quantum techniques to calculate the protein-ligand binding energy **for the BACE1 enzyme, which has been linked to Alzheimer's disease pathogenesis.**
- In order to perform energy calculations, we combine a numerical method density matrix embedding theory (DMET) embedding method for solving strongly correlated electronic structure problems with a variational quantum eigenvalue solver (VQE) approach for finding electronic ground states of molecules.
- The machine used the following two
  - ✓ **IBM superconducting quantum computer**
  - ✓ **Quantinuum (formerly Honeywell Quantum Solutions) ion trap quantum computer (NISQ)**

Expected business benefits

- The previous method used a quantum emulator, but this verification was able to **calculate protein-ligand binding energy for the first time using an actual quantum computer**
  - ✓ **NISQ's quantum computer** showed that we could calculate the binding energy of a protein **- ligand.**

Reference: arXiv"Quantum Computational Quantification of Protein-Ligand Interactions" (https://arxiv.org/pdf/2110.08163)

Finance

Combinatorial Optimization	Portfolio optimization of liquid assets	P94
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NatWest: Portfolio optimization of liquid assets [2018/10]

Industry	Finance
Process	bank
Method	combinatorial optimization

Background

- Financial institutions should ideally incorporate liquid and creditworthy assets, including cash, bonds and government bonds, to provide the greatest possible return while maintaining an acceptable level of risk
- However, they are **constantly faced with the challenge of creating and maintaining an optimal portfolio of assets from thousands of options.**
- While liquid assets are of paramount importance to financial institutions, **the calculations for combinatorial optimization of assets have been too complex, costly and time-consuming to do often.**

Issues and motivation to be solved

- The vast array of options **promises to use quantum technology to create and maintain an optimal portfolio of assets**
- NatWest **designed a demonstration experiment to solve the combinatorial optimization problem of a financial portfolio at high speed using Fujitsu's quantum technology**

Problem setting as a quantum computer

- Calculated NatWest Bank's **high-quality liquid assets** * and **optimal portfolio composition for (HQLA)**
  - ✓ HQLA is an asset such as cash or bonds that all banks in the UK need to hold as a buffer in the event of financial difficulties
- The machine uses **Fujitsu digital annealer**

Expected business benefits

- Ability to **compute combinatorial optimization problems about 300 times faster** than conventional classical computers.
- The use of quantum technology will **make it possible to be accurate and reduce the risk of human error.**
- In addition, NatWest is expected to be able to complete a comprehensive risk assessment of the Bank's portfolio at a high speed and to **optimize the interest rate spread, which is the difference between the lending rate and the deposit rate, and reduce risk,** by enabling a much wider range of results and portfolio replacements than in the past.

*: A safe asset that can be easily sold in times of market stress. last line of defense for financial institutions in dealing with liquidity risk

Reference: Fujitsu Limited "Demonstration of "digital annealer" at Fujitsu and Royal Bank of Scotland group NatWest" (https://pr.fujitsu.com/jp/news/2018/10/23-1.html)

MELCO INVESTMENTS: Optimizing stock investment portfolio【2020/02】

Practical Application

Industry	Finance
Process	securities
Method	combinatorial optimization

Background

- What is important in investment and asset management is the balance between return and risk. When choosing an investment destination, it is important to seek a large return while preparing for possible sudden price fluctuations. One of the measures is **diversification through a financial asset portfolio.**
- In order to select a portfolio by combining the most appropriate financial products, **it is necessary to examine the composition ratio of financial products by quickly analyzing and judging the ever-changing financial conditions of companies and market trends.**
- The financial asset portfolio **has a large number of combinations** depending on the number of issues handled

Issues and motivation to be solved

- In order to optimize the portfolio of financial assets, **For example, to select 50 stocks from 100 stocks, 10^29 combinations are required, which is difficult to calculate with conventional classical computers.**
- MELCO INVESTMENTS **attempted to reduce computation time by solving the portfolio optimization problem of financial assets using quantum technology**

Problem setting as a quantum computer

- **Evaluate the calculation time for the portfolio optimization problem of financial assets** based on stock data (several hundred stocks) and constraints
- Machine utilizes **Fujitsu digital annealer**

Expected business benefits

- Ability to **calculate an optimal portfolio of financial assets in about 10 minutes** for hundreds of stocks
  - ✓ This is the first practical application of digital annealer in the financial sector.

Reference: Fujitsu Limited "In an Age of Uncertainty, Challenges Faced by Enterprises Are Solved by Digital Annealer" (https://www.fujitsu.com/jp/digitalannealer/news/202103-article/)

Hitachi: Optimization of arbitrage in financial instruments (2021/10) 1/2

Industry: Finance
Process: securities
Method: combinatorial optimization

Background

- Hitachi is working to create services to improve customer business resilience against rapid changes in the business environment.
  - ✓ In financial transactions, for example, **it is necessary to solve a combinatorial optimization problem that takes various options into account in response to an ever-changing environment.**
- Hitachi has developed CMOS annealing as a technique for solving combinatorial optimization problems, and has applied it to customer business problems such as reinsurance portfolio optimization of non-life insurance and work shift optimization in call centers.
- This time, by utilizing the features of CMOS annealing suitable for combinational optimization processing, we will work on **portfolio optimization to support arbitrage of financial products** *1

Issues and motivation to be solved

- Financial instruments can bring large profits, but they also have the risk of falling in value. Instead of investing all funds in a single financial instrument, diversified investments are made by combining multiple financial instruments to reduce risks. **It is important to construct an optimal portfolio that balances profits and risks.**
- Conventional statistical methods combine multiple stocks to construct a portfolio of financial instruments with average reversion, *2. However, it is important to consider such constraints and indicators as trading rule constraints such as transaction fees and positions for each stock constituting the portfolio, and liquidity risk.

*1: A transaction in which profits are made by using the price difference between the financial instruments to be bought and sold
*2: A property that approaches the average value over time

Reference: Hitachi Group, Ltd. "Technology for Applying CMOS Annealing Suitable for Combinatorial Optimization Processing to High-Speed Financial Instruments Trading and Development of" (https://www.hitachi.co.jp/rd/news/topics/2021/2110_cmos.html), Mitsui https://www.mki.co.jp/knowledge/column128.html Information Corporation How will quantum computers change finance?

Hitachi: Optimization of arbitrage in financial products [2021/10] 2/2

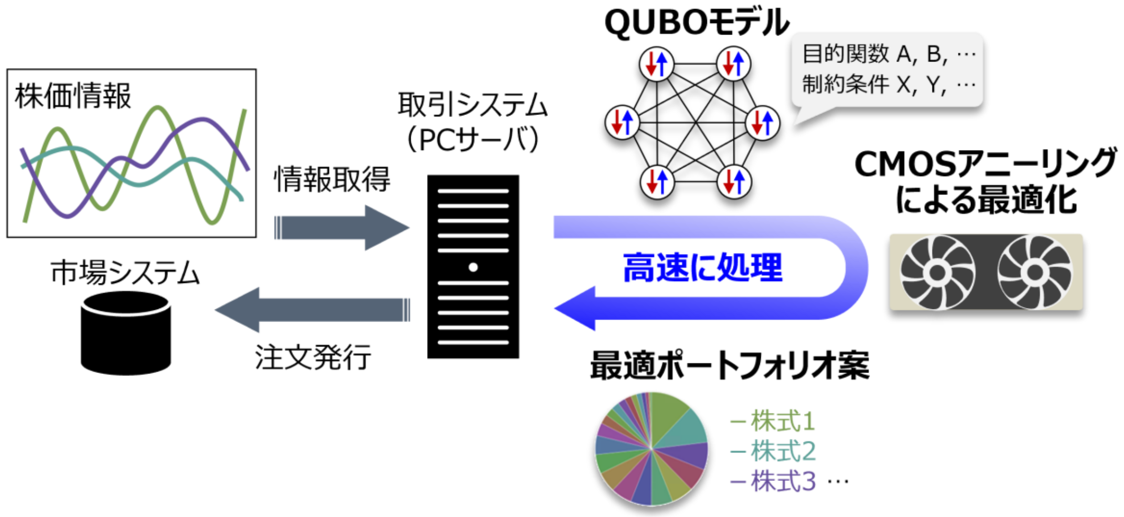
Industry	Finance
Process	securities
Method	combinatorial optimization

Problem setting as a quantum computer

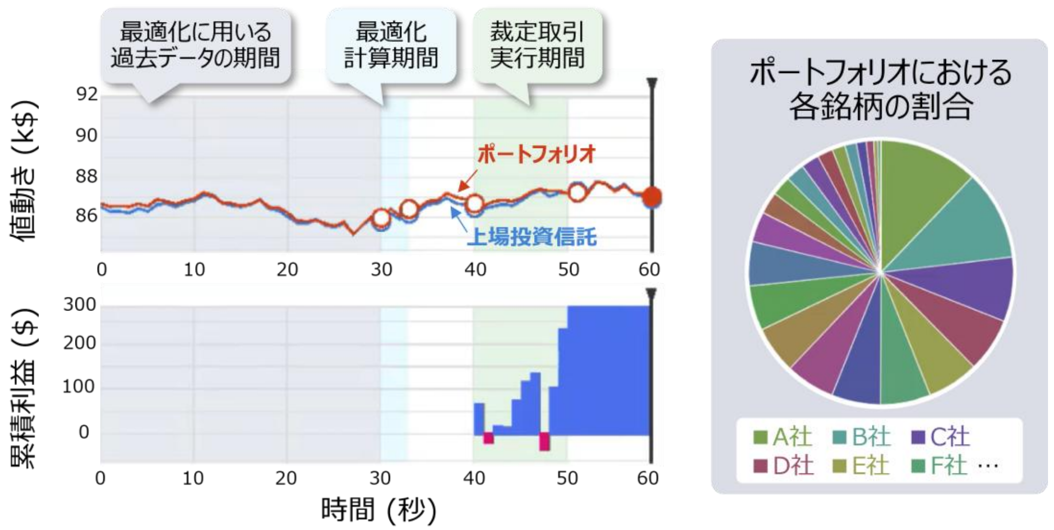
- **By writing down the matters to be considered in arbitrage as objective functions and constraints in QUBO form**, the problem of finding the optimal portfolio of financial instruments with mean reversion property is formulated.
  - ✓ Rules for buying and selling such as transaction fees and positions for each stock in the portfolio
  - ✓ Indicators: Liquidity risk, etc.
- The machine leverages **Hitachi CMOS annealing**

Expected business benefits

- **In CMOS annealing, as long as the number of variables is unchanged, the computation time does not change, and arbitrage trading is both practical and fast.**
- An assessment using historical transaction data was conducted to verify the effectiveness of the indicators and constraints considered in arbitrage
- By performing a valuation using approximately 100 stocks while switching historical data, we were able to confirm that CMOS annealing **can construct an optimal portfolio within a few seconds and use it to make arbitrage returns.**



High-Speed Financial Instruments Trading System Using Cmos Annealing



Screen of transaction simulation results in conjunction with CMOS annealing

Reference: Hitachi Group "Development of CMOS annealing technology suitable for combinatorial optimization processing for high-speed financial instruments trading" (https://www.hitachi.co.jp/rd/news/topics/2021/2110_cmos.html)

Goldman Sachs AWS: Estimated Resources Required for Portfolio Optimization (2023/11)

Background

- One commonly studied use case in the quantitative finance space is portfolio optimization
- A quantum algorithm for solving portfolio optimization has been proposed, **which is expected to provide theoretical speedups compared to classical algorithms.**

Issues and motivation to be solved

- As quantum technology is expected to be used to solve portfolio optimization problems, **it is difficult to evaluate whether quantum computers can be used to theoretically achieve higher speeds, but it is important to estimate the number of qubits and other factors required to achieve such speeds.**
- Despite the difficulty, Goldman Sachs and AWS worked together to **estimate the quantum computer resources needed to solve portfolio optimization.**

Problem setting as a quantum computer

- **Build a portfolio that maximizes expected returns while minimizing the likelihood of risk deviating from expected values**
- The classical method widely used to solve portfolio optimization, the **Interior Point Method * (IPM), is replaced with the quantum interior point method (QIPM) using quantum technology and speed up is achieved.**
- **Estimate QIPM Quantum Resources** Based on the Number of stocks

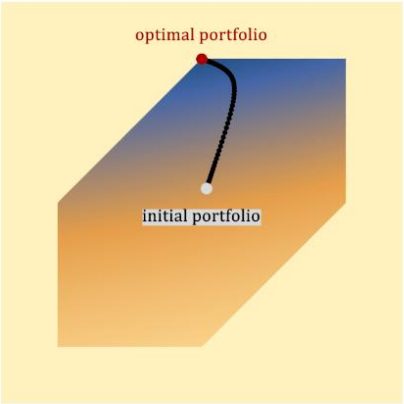


Diagram of Interior Point Method Solving Portfolio Optimization

Expected business benefits

- Based on an estimate of quantum computer resources with the number of stocks set at 100, it was shown that **8 million logical qubits are needed**
- **Quantum algorithms are still running in millions of years,** according to the estimates
- In the case of QIPM, they show that **it is not useful unless there is a significant improvement in the underlying algorithm,** and it has become clear that there are still significant challenges to its practical use.

*: An algorithm for optimization problems, characterized by convergence to optimization through feasible regions.

Reference: AWS"A detailed, end-to-end assessment of a quantum algorithm for portfolio optimization, released by Goldman Sachs and AWS" (https://aws.amazon.com/jp/blogs/quantum-computing/a-detailed-end-to-end-assessment-of-a-quantum-algorithm-for-portfolio-optimization-released-by-goldman-sachs-and-aws/)

Sompo Group: Non-Life Insurance Portfolio Optimization (2020/01)

Practical Application

Industry	Finance
Process	Insurance
Method	combinatorial optimization

Background

- In recent years, the non-life insurance industry has seen **an increase in insurance claims payments due to the frequent occurrence of large-scale natural disasters in Japan and overseas, and it is important to deal with larger-than-expected losses resulting from natural disasters**
- Sompo Japan Nipponkoa and Sompo Risk Management have been working on using the natural disaster engineering model and portfolio optimization technology developed by Sompo Japan, **reinsurance,** *1, and **efficiently utilizing the mechanism to distribute risks held by non-life insurance companies to outside parties such as reinsurance companies, to appropriately distribute natural disaster risks, and to conduct stable insurance management.**

Issues and motivation to be solved

- In addition to the large-scale natural disasters that have frequently occurred in recent years, changes in the business environment such as overseas business expansion have led to an increase in **the number of insurance policies and insurance schemes to be considered, and the need for larger and more complex non-life insurance portfolio optimization.**
- Since **solving the non-life insurance portfolio optimization problem considering large-scale and complicated insurance conditions on a classical computer takes a huge amount of calculation time on a monthly or yearly basis,** we verify whether the optimization problem can be solved within an acceptable calculation time by using CMOS annealing.

Problem setting as a quantum computer

- In order to solve the non-life insurance portfolio optimization problem considering large-scale and complicated insurance conditions, we modeled the following conditions and **developed a method to obtain conditions compatible with risk-taking and stable earnings from a large number of combinations.**
  - ✓ Risks to be held by Sompo Japan Insurance
  - ✓ Risks that should be transferred externally, such as reinsurance
  - ✓ Conditions at the time of transfer (reinsurance conditions)
  - ✓ Other conditions that need to be considered in practice
- The machine leverages **Hitachi CMOS annealing**

Expected business benefits

- This time, we **verified whether it is possible to solve the non-life insurance portfolio optimization problem within the allowable calculation time (e.g., within one day)** considering large-scale and complicated insurance conditions.
- After repeated verification of the feasibility of CMOS annealing, **the prospect of practical use became clear, and in April 2022 we started practical use of CMOS annealing in non-life insurance underwriting**

*1: Insurance companies non-life insurance that distributes risk by transferring part or all of the responsibility for insurance contracted with policyholders to other insurance companies

Reference: Sompo Japan Insurance "Began demonstration of non-life insurance portfolio optimization using a new semiconductor-based computer" (https://www.sompo-japan.co.jp/-/media/SJNK/files/news/2019/20200108_1.pdf), Sompo Japan Insurance "Sompo Japan Starts Practical Use of Quasi-Quantum Computers in Insurance Underwriting" (https://www.sompo-japan.co.jp/-/media/SJNK/files/news/2021/20220329_3.pdf)

Sumitomo Mitsui FG: Creating optimal work shifts at call centers【2020/10】1/2

Practical Application

Industry	Finance
Process	Insurance
Method	combinatorial optimization

Background

- In Japan, where the working population is decreasing year by year, call centers in various industries, such as finance, are facing an **urgent operational challenge** to continue providing high-quality services to inquirers even though the number of operators is limited.
- In order to solve operational problems, it is necessary to allocate operators appropriately in order to predict the volume of inquiries. However, in many cases, simply allocating the number of operators is not sufficient. **In practice, it is necessary to consider staffing after considering the skills of each operator, desired shifts, paid holidays, etc.**

Issues and motivation to be solved

- The person in charge of creating shifts spends an enormous amount of time and effort to create work shifts every month while considering various conditions such as the operator's skill, desired shift, and vacation schedule. However, **there is a problem that it is not possible to flexibly reflect the operator's wishes and situation because there is a limit to creating shifts by hand, and that there is a problem that there is an excess or shortage of the number of workers originally required.**
- In order to create optimal work shifts using CMOS annealing, we planned to **examine and demonstrate the practical evaluation viewpoint of CMOS annealing at several call centers of SMFG.**

Expected business benefits

- Compared to conventional work shifts created manually, **high effectiveness in optimizing personnel allocation was confirmed, such as reducing the occurrence of redundant assignments by approximately 80%.**
- Optimized staffing **can be expected to prevent increased costs due to overstaffing, delayed response due to staff shortages, and reduced service quality.**

Reference: Hitachi, Ltd. "Offers solutions to create optimal work shifts for tens or hundreds of employees" (https://www.hitachi.co.jp/New/cnews/month/2020/10/1019a.html) and Work Shift Optimization Solution (https://www.hitachi.co.jp/products/it/finance/solutions/application/common/CMOS-PersonnelShift/index.html)

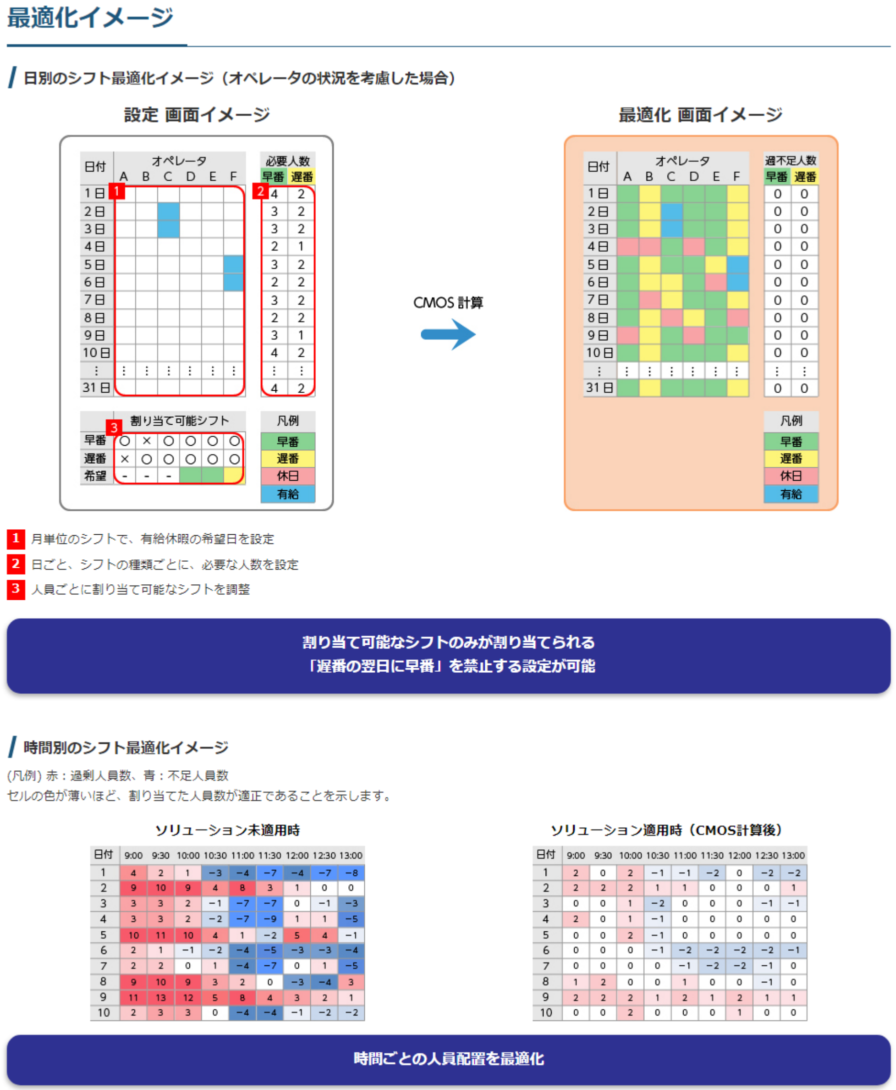
Sumitomo Mitsui FG: Creating optimal work shifts at call centers [2020/10] 2/2

Practical Application

Industry	Finance
Process	Insurance
Method	combinatorial optimization

Problem setting as a quantum computer

- In large-scale work shifts such as in call centers, **optimal personnel allocation is realized by taking into account detailed operator constraints in a complex manner** instead of uniform rotation.
  - ✓ Hourly number of people and tasks (duties)
  - ✓ leave request
  - ✓ frequency of work
  - ✓ commuting time
- The machine leverages **Hitachi CMOS annealing**



Reference: Hitachi, Ltd. "Offers solutions to create optimal work shifts for tens or hundreds of employees" (https://www.hitachi.co.jp/New/cnews/month/2020/10/1019a.html) and Work Shift Optimization Solution (https://www.hitachi.co.jp/products/it/finance/solutions/application/common/CMOS-PersonnelShift/index.html)

Singapore Management University, etc.: Credit Scoring for SMEs (2024/01) 1/2

Industry: Finance
Process: bank
Method: AI

Background

- credit scoring facilitates economic expansion by allowing companies to borrow capital at reasonable rates
- Large companies were given credit ratings by many analysts, but **small and medium-sized companies (SME) were less analyzed by rating agencies and credit scoring was based only on company and market data.**
- More recently, the use of machine learning approaches has enabled **automated credit scoring that combines enterprise, accounting, and socioeconomic information to provide broader coverage of SME attributes.**

Issues and motivation to be solved

- **Improving machine learning algorithms used in credit scoring is important to provide credit risk transparency.**
- The researchers, who include members of Singapore Management University, worked on **a machine learning algorithm that leverages quantum technology to enhance credit scoring for SMEs**.

Problem setting as a quantum computer

- To perform credit scoring for SMEs, one conducts **a quantum and classical hybrid model using quantum techniques on a real test dataset of Singapore companies**
- As test data, 246 defaulting companies and 2,000 healthy companies were used **for 2,246 companies incorporated between 1940 and 2016.**
- In order to compare the classical model with the model using quantum technology, we performed **accuracy comparison according to the number of repetitions (epochs) of the whole training data**
- The machine utilizes a **gate system (simulator)**

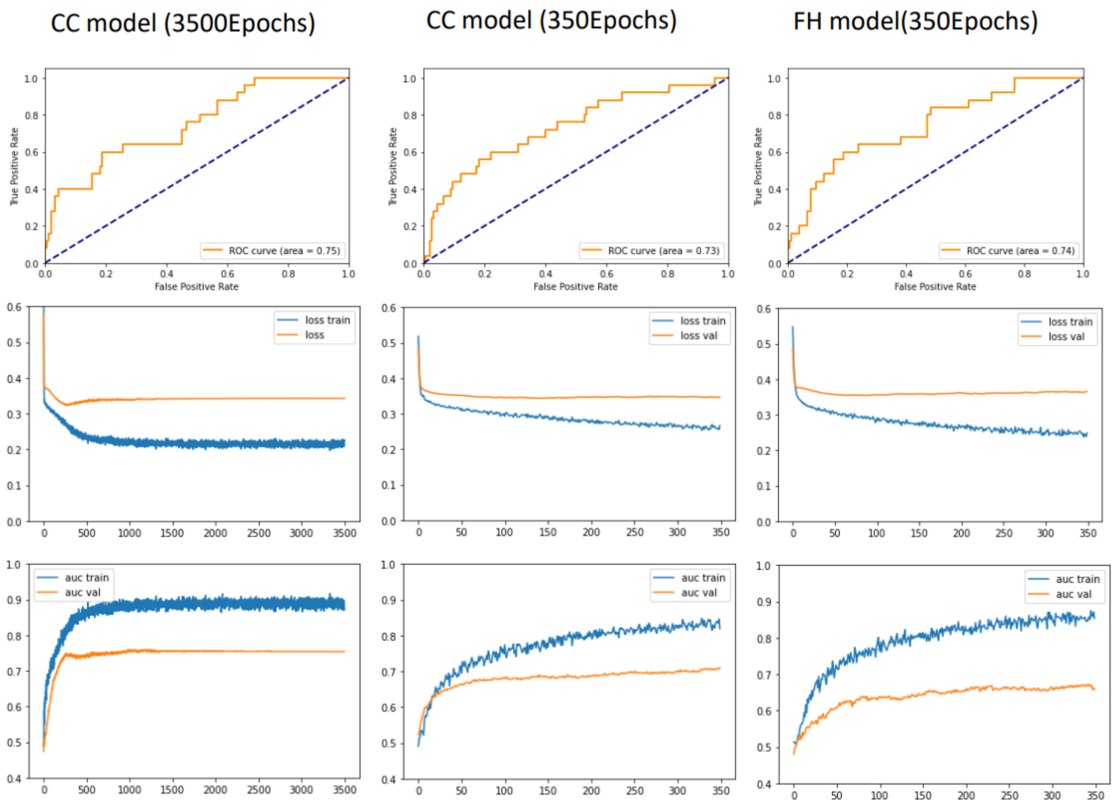
Reference: MDPI"Quantum Machine Learning for Credit Scoring" (https://www.mdpi.com/2227-7390/12/9/1391)

Singapore Management University, etc.: Credit Scoring for SMEs (2024/01) 2/2

Industry	Finance
Process	bank
Method	AI

Expected business benefits

- The quantum-classical hybrid model (FH model) achieved significantly less **similar prediction accuracy with 1/10 epochs** than the conventional CC model with 3,500 epochs
- When compared with the conventional method at the same number of epochs (350), it was found that **higher accuracy than the conventional method** was obtained.



Reference: MDPI"Quantum Machine Learning for Credit Scoring" (https://www.mdpi.com/2227-7390/12/9/1391)

Aioi Nissay Dowa (USA) ・AWS: Driving risk prediction based on vehicle sensor data 【2021/05】

Industry Finance

Process Insurance

Method AI

Background

- Aioi Nissay Dowa (USA) is promoting the **development of data science-based products and services for the transportation industry.**
- Since vehicles are equipped with a number of sensors that collect data, we would like to perform **vehicle driving risk assessment using sensor data.**
- In order to assess risk, **a method using a binary classifier** is being considered for classifying data by assigning binary labels (0 or 1, Safe or Fail, etc.) to input data.

Issues and motivation to be solved

- One machine learning technique used to classify data is deep learning, and **it is an open question whether quantum neural networks (QNN) powered by quantum technology have a practical computational advantage over classical neural networks.**
- Aioi Nissay Dowa (USA) and AWS conducted **a validation to predict driving risk using vehicle telematics data using quantum machine learning**

Problem setting as a quantum computer

- **Using vehicle telematics data, perform machine learning and validate to predict driving risk** with autonomous driving levels L1 and L2*
- **QNN using quantum technology** is used as the machine learning circuit
- The machines are powered by **Amazon Braket,** AWS's quantum computing service.

Expected business benefits

- Using quantum machine learning, **By combining QNN with the Amazon Braket quantum computing service, we were able to show how to analyze vehicle telematics data**.

*L1 is the driving assistance (Automatic braking, follow the car in front of you (ACC), stay out of the vehicle (LKAS)) and L2 is the automated driving function under specific conditions (L1 combination)

Reference: AWS"Using Quantum Machine Learning with Amazon Braket to Create a Binary Classifier" (https://aws.amazon.com/jp/blogs/quantum-computing/aioi-using-quantum-machine-learning-with-amazon-braket-to-create-a-binary-classifier/), Magnica "What are the levels of autonomous driving? Explains all the way up to level 0~5" (https://www.macnica.co.jp/business/maas/columns/135343/)

SMBC: Application Ad Analysis for Advanced Ad Delivery (2025/10)

Industry	Finance
Process	bank
Method	AI

Background

- The mainstream of quantum computation is hybrid use with conventional computation, and it has strength in combinatorial optimization, and its application is advancing in marketing and finance.
- In the advertisement distribution through smartphone apps, there is a lot of room to improve targeting accuracy through advanced analysis, since a variety of high-dimensional features such as customer attributes and behavior logs are linked.

Issues and motivation to be solved

- The objective is to apply an approach such as feature quantity selection utilizing quantum computers to the advertisement distribution area and compare it with the conventional machine learning only method and confirm the effect.
- We verified the effectiveness of quantum AI in the financial and advertising domains by demonstrating greater accuracy and explainability than conventional machine learning-only methods. Verify reproducibility and versatility for future category expansion

Problem setting as a quantum computer

- Demonstration using a combination of quantum AI technology and conventional machine learning models for analysis and recommendation of advertisement delivery in SMBC's smartphone apps
- Verification of the effectiveness of quantum AI technology that combines quantum computer and machine learning, such as feature quantity selection using analysis method of quantum computer

Expected business benefits

- Gradually expand target data and advertising categories to verify reproducibility and versatility
- Application of Advanced Quantum AI Algorithms to Financial and Advertising Fields
- Creating new value through practical solutions that combine quantum computing and AI

Reference: Sumitomo Mitsui Banking Corporation: "Demonstration of Application Advertising Analysis Using Quantum Computers by Sumitomo Mitsui Banking Corporation, SMBC Digital Marketing Corporation, and Quanmatic Corporation" (https://www.smbc.co.jp/news/pdf/j20251031_01.pdf)

Keio University, Mizuho, IBMMUFG: Monte Carlo Simulation for Derivative Pricing【2019/04】

Background

- The financial industry runs **a large number of high-performance computers (classical computers) and performs various calculations.**
  - ✓ For example, for a financial product, **the price is calculated by computer over several hours at night to determine the price of the product the next day.**
- "Options trading," one type of derivatives, involves trading the "right" to buy and sell financial instruments such as stocks and bonds at a predetermined price, but **this price is calculated in large quantities every day by high-performance computers.**

Issues and motivation to be solved

- **One spends more than a few hours at night doing calculations on the computer, and the challenge is to speed up those calculations.**
- **Monte Carlo calculation** are used to calculate prices and since this is one of the calculations that are said to have advantages by using quantum computers, **financial institutions around the world are conducting research**
- **Keio, Mizuho, IBM-MUFG collaborated in joint research** to speed up Monte Carlo calculations.

Expected business benefits

- By eliminating the quantum Fourier transform, the number of qubits did not increase, and **the number of quantum gates was reduced by nearly 90%.**

Problem setting as a quantum computer

- The challenge is to calculate the price of an option trade, **one of derivatives, at high speed.**
- use an **amplitude estimation algorithm** to perform Monte Carlo calculations
  - ✓ To compute the amplitude estimation algorithm, an operation called quantum Fourier transform was necessary, but **a statistical method of post-processing on a classical computer eliminates the need for quantum Fourier transform and shortens the circuitry of the quantum computer.**

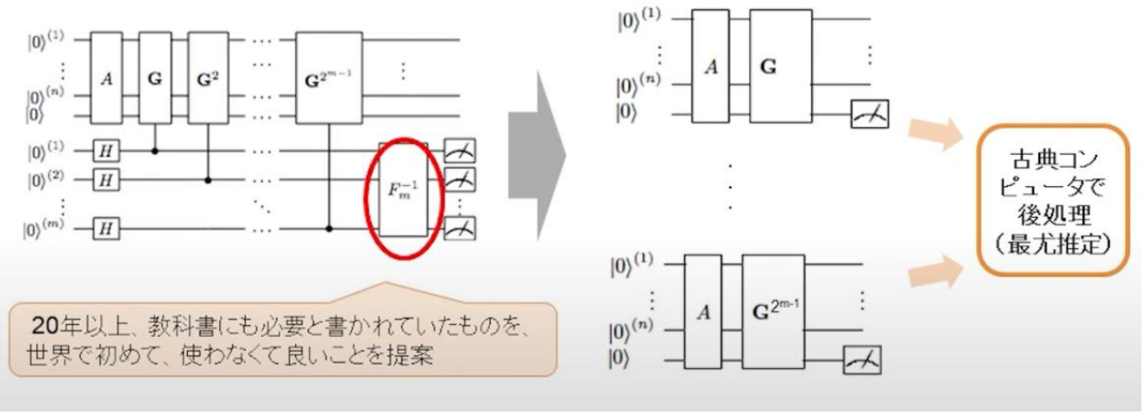


Image of the amplitude estimation algorithm

Reference: Tokyo Stock Exchange Management Department "Why finance firm MUFG is studying quantum computers", (https://money-bu-jpx.com/news/article028387/), FINOLAB CHANNEL"Why finance firm MUFG is studying quantum computers" (https://www.youtube.com/watch?v=MOkSZ-cWCG0)

HSBC: Financial Transaction Close Forecast (2025/11)

Industry: Finance
Process: securities
Method: Simulation

Background

- An important element of algorithmic bond trading is the accurate prediction of which orders will lead to contracts, but it is limited by the complex dynamics of financial markets with inherent uncertainty and by models that aim to learn from multivariate financial time series that exhibit stochastic properties, often with hidden temporal patterns
- HSBC and IBM experiment with a quantum-classical hybrid method on IBM Quantum Heron processors using utility-scale intraday event data

Issues and motivation to be solved

- Higher accuracy of contract probability estimation in algorithmic bond trading using hybrid method is desired.

Problem setting as a quantum computer

- Combining quantum and classical computing resources to analyze HSBC's utility-scale bond trading data
- Predicting which transactions will be closed using a quantum-classical hybrid method
  - Up to 34% improvement over the classical computer only approach

Expected business benefits

- demonstrate the potential of current and near-future quantum computers to give financial services companies a significant competitive advantage in this valuable use case
- It's an example of how IBM's partners can combine their deep expertise with the latest innovations in quantum algorithm development to demonstrate the utility of quantum computers in practical applications.

See Also: HSBC: "HSBC breaks new ground with IBM quantum computer algorithm deal" (https://www.ibm.com/jp-ja/think/insights/hsbc-quantum-algorithmic-bond-trading)

Transportation

Combinatorial Optimization	Traffic flow optimization (congestion reduction)	P109
	Optimization of Traffic Signals in Large Cities	P113
	Multimodal Transport System Route Optimization	P115
	Optimizing human flow for disaster damage control	P117
	Traffic control for flying cars (air mobility)	P118
	Sea route optimization	P120
	Optimization of delivery planning	P121
	Delivery to multiple areas by sharing trucks among multiple stores	P123
	Railway scheduling optimization	P125
	Optimization of maintenance parts delivery plan	P126

Volkswagen: Traffic flow optimization (congestion reduction) [2019/11] 1/4

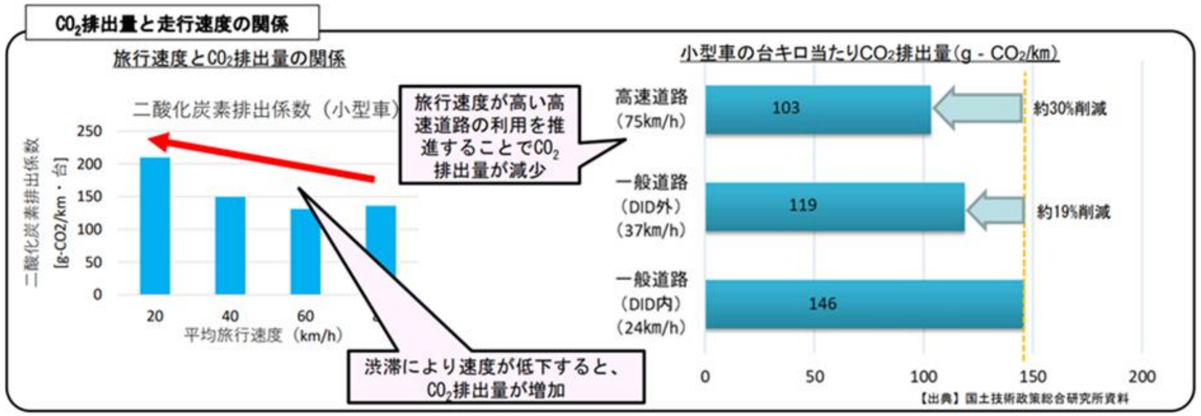
Industry: Transportation

Process: Human Movement _ Land Transport

Method: combinatorial optimization

Background

- **Traffic congestion in urban areas with a high density of vehicles on the road is one of the causes of global warming due to emissions of air pollutants such as NOX (nitrogen oxides) and carbon dioxide, as well as economic losses caused by longer travel times for passengers.**
  - ✓ CO2 emissions increase due to slower speeds and longer driving times caused by traffic jams
- **By developing means and technologies to "avoid traffic congestion before it becomes apparent," it will be possible to reduce exhaust gas emissions from low-speed driving and wasteful fuel consumption such as idling.**
  - ✓ It is important not only to solve environmental problems but also to improve convenience by shortening travel time for vehicle users.



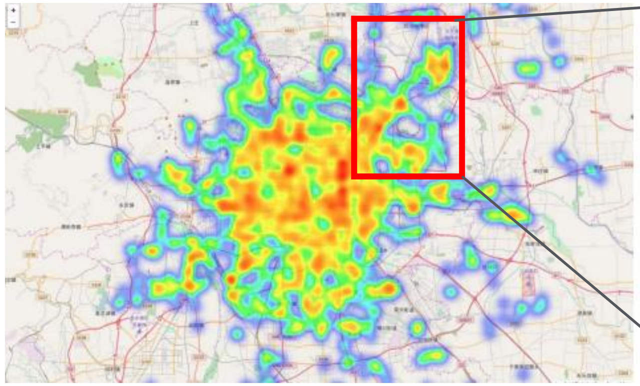
Reference: the Ministry of Land, Infrastructure, Transport and Tourism "Contribution to Carbon Neutrality in the Road Sector" (https://www.mlit.go.jp/policy/shingikai/content/001470072.pdf) and D-WAVE"How Volkswagen is using real quantum computers for transportation optimization research" (https://dwavejapan.com/app/uploads/2019/12/Final_Dwave_VW_Case_Study_2019_11_13.pdf)

Volkswagen: Traffic flow optimization (congestion reduction) [2019/11] 2/4

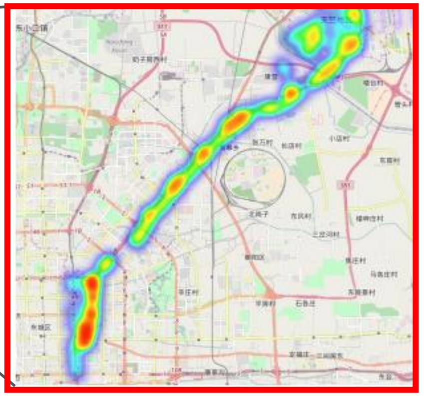
Industry	Transportation
Process	Human Movement _ Land Transport
Method	combinatorial optimization

Issues and motivation to be solved

- **Solving congestion in urban areas To solve the traffic flow optimization required, it is necessary to solve the route optimization problem considering millions of vehicles and billions of routes and destinations.**
  - ✓ In particular, when handling a plurality of vehicles connecting two points, all vehicles tend to take the same (shortest) route connecting the two points, resulting in congestion.
- Therefore, it is necessary to control the travel route of multiple vehicles traveling at the same time in order to solve the congestion. Therefore, it is important to verify the effectiveness of the combinatorial optimization that selects the optimal route including the route which is not congested from the location data collected in real time.
  - ✓ On the other hand, computation with a large number of parameters is difficult with classical computers.
- Volkswagen has demonstrated how to use quantum computers to improve utilization.



large cities with heavy traffic jams (e.g. Beijing)
(High vehicle density in red)



Traffic congestion on the route between two points (between Beijing City and Beijing International Airport)

Reference: D-WAVE"How Volkswagen is using real quantum computers for transportation optimization research" (https://dwavejapan.com/app/uploads/2019/12/Final_Dwave_VW_Case_Study_2019_11_13.pdf), VOLKSWAGEN"Quantum Computing at Volkswagen: Traffic Flow Optimization using the D-Wave Quantum Annealer" (https://www.dwavesys.com/media/erzjluvs/qubits-day-2-morning-5-vw.pdf)

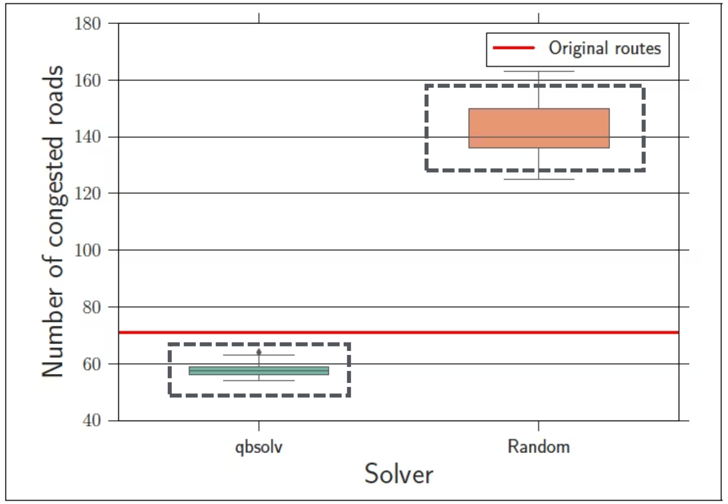
Volkswagen: Traffic flow optimization (congestion reduction) [2019/11] 3/4

Industry	Transportation
Process	Human Movement _ Land Transport
Method	combinatorial optimization

Problem setting as a quantum computer

- The demonstration will focus on optimizing the traffic flow of taxis between Beijing and Beijing International Airport in China, which is the most congested city in the world (instead of alleviating the congestion of the entire city), and will **derive an optimized route for eliminating congestion by collecting travel data from moving vehicles**.
- The machine is powered by a **quantum annealing machine** from D-Wave.

problem setting	• Elimination of traffic jams by taxis connecting the congested city center and Beijing Airport (= optimization of traffic flow by distributing routes)
quantum computer Hardware	• D-wave2000Q (2000 qubits)
Implementation	• Update the taxi route by executing the following optimization calculation 50 times
objective function	• Reduce route overlap as much as possible for the 418 optimized taxis (allowing longer routes)
Constraints	• Each taxi must choose one route
Variables	• **418 taxis x 3 possible routes =1,254 variables** • (Since it exceeds the logical variables that can be solved by a D-Wave machine with limits between qubits, it is calculated by a hybrid classical/quantum computer tool.)→ **The number of combinations is 3 ^ 418**



Solver:
qbsolv is a quantum algorithm, Random is a random route assignment to a taxi
Number of congested roads

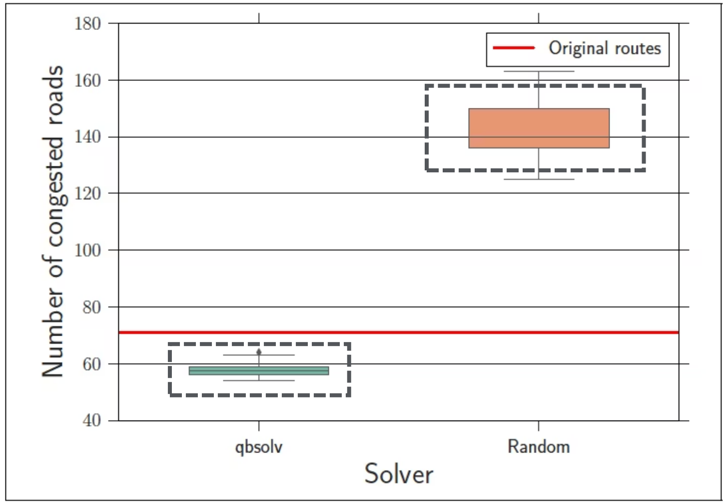
Reference: D - WAVE "How Volkswagen is using real quantum computers for transportation optimization research" (https://dwavejapan.com/app/uploads/2019/12/Final_Dwave_VW_Case_Study_2019_11_13.pdf)

Volkswagen: Traffic flow optimization (congestion reduction) [2019/11] 4/4

Industry	Transportation
Process	Human Movement _ Land Transport
Method	combinatorial optimization

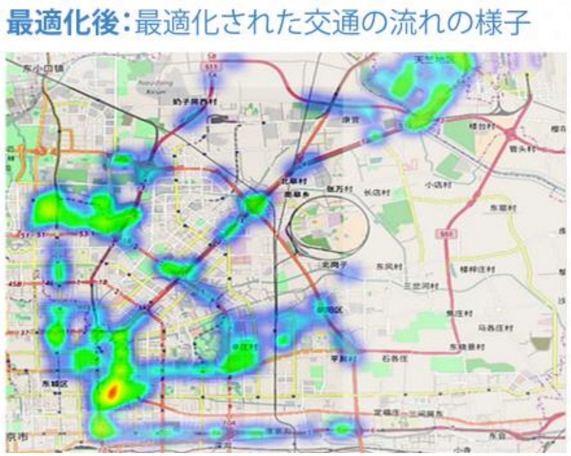
Expected business benefits

- The effect of a quantum annealing machine (D-wave2000Q) and a classical/quantum hybrid algorithm for route optimization on reducing taxi congestion was measured using open maps.
- Using GPS data from 418 Beijing taxis (updated every 1 to 5 seconds) to calculate optimized routes in real time, **we demonstrated that we could distribute routes for each vehicle and reduce congestion.**



Solver:
qbsolv is a quantum algorithm, Random is a random route assignment to a taxi
Number of congested roads

If all taxis take the same route, there are many congested roads (red areas on the map) where taxis are concentrated.



Quantum-Computer Algorithms Allocate Alternate Routes to Taxis and Eliminate Congested Areas

Reference: D - WAVE "How Volkswagen is using real quantum computers for transportation optimization research" (https://dwavejapan.com/app/uploads/2019/12/Final_Dwave_VW_Case_Study_2019_11_13.pdf)

Toyota Central Research Institute/University of Tokyo: Optimization of Traffic Signals in Large Cities【2021/02】1/2

Industry Transportation
Process Human Movement _ Land Transport
Method combinatorial optimization

Background

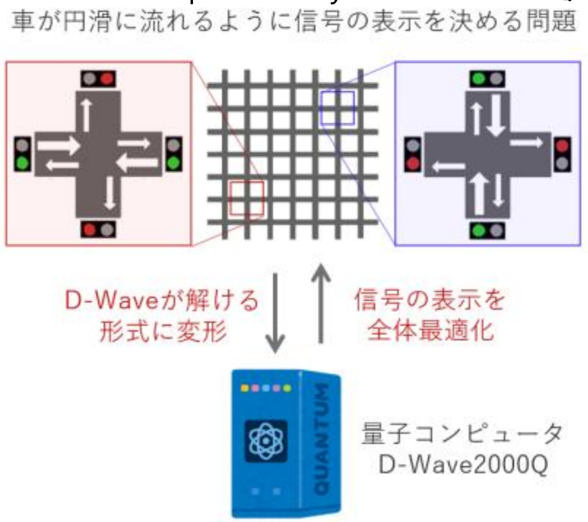
- **Adaptive control of traffic signals according to traffic conditions is an important issue** to alleviate congestion in large cities.
- Traffic light control in large cities is a complex problem, and optimizing the overall traffic flow to minimize the likelihood of traffic congestion **is almost impossible with traditional Methods.**
- Various workarounds have been proposed, most of which are **local control methods** that divide the network into smaller pieces and control each signal using only information about the neighborhood of the intersection

Issues and motivation to be solved

- Traditional traffic light control only considers local information around each intersection, **not a way to simultaneously optimize traffic conditions for the entire city.**
- The Toyota Central Research Institute and the University of Tokyo jointly **planned to develop a method to control traffic signals in large cities in consideration of traffic conditions throughout the city.**

Problem setting as a quantum computer

- Developed a method to solve the **traffic signal optimization problem** considering the traffic conditions of the entire city using quantum technology
  - ✓ **An optimization problem is solved to determine the state of traffic lights at each intersection so as to minimize the traffic flow bias.**
- **Road networks are vertically and horizontally orthogonal grids,** and **traffic on the road network is modeled by a group of vehicles turning right and left with a certain probability.**
- A numerical experiment was conducted to simultaneously control traffic signals in a city consisting of 50×50 roads, and **the value of the evaluation function representing the magnitude of traffic flow deviation was compared with the conventional method**
- The machine is powered by **D-Wave 2000 Q,** D-wave quantum annealing.



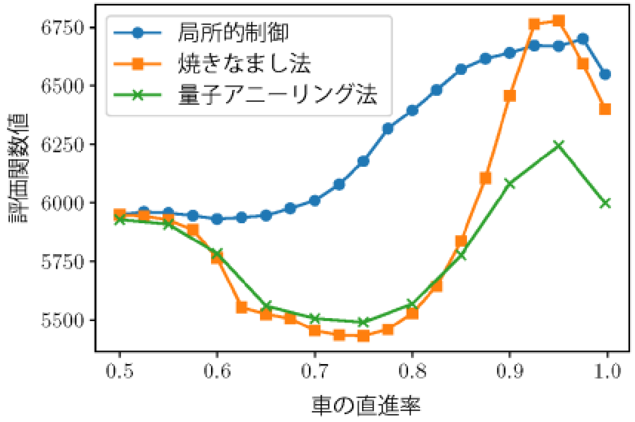
Conceptual diagram of traffic flow control method

Reference: The University of Tokyo, "Successful Development of Optimization Technology for Controlling Large Traffic Signals Using Quantum Computers" (https://www.tytlabs.co.jp/cms/news/pdf/press/20210210_%20press.pdf)

Toyota Central Research Institute/University of Tokyo: Optimization of Traffic Signals in Large Cities【2021/02】2/2

Expected business benefits

- As a result of comparing a conventional method with a method using quantum technology, we were able to **improve the ease of traffic flow by approximately 10%**
- It was also found that **the quantum annealing machine is faster and more efficient than the annealing method,** although the conventional optimization method, the annealing method, can be used.
- This result **is expected as a basic technology to control traffic lights in real cities at high speed and efficiently according to the traffic conditions of the whole city.**



Comparison of evaluation function values representing the magnitude of traffic flow deviation
(Small value of evaluation function = smooth traffic flow)

Reference: The University of Tokyo, "Successful Development of Optimization Technology for Controlling Large Traffic Signals Using Quantum Computers" (https://www.tytlabs.co.jp/cms/news/pdf/press/20210210_%20press.pdf)

Denso: Multimodal Transport System Route Optimization "2023" 1/2

Industry: Transportation
Process: Human Movement _ Land Transport
Method: combinatorial optimization

Background

- Taxis and ride-hailing services have become **essential transportation to get around many cities around the world.**
  - ✓ Tourists are heavy users of taxis, and many use them as sightseeing opportunities on their way to their destinations.
- But when it comes to ride-hailing, **it's hard to get enough vehicles at the right place and time to minimize the time wasted by both drivers and waiting passengers.**

Issues and motivation to be solved

- Denso is one of the world's leading manufacturers of automotive components, and **the technology that enables connected driving is important.**
- Denso **planned two demonstrations using quantum technologies to improve the efficiency and sustainability of urban transport.**
  - ✓ Optimization of the number of taxis
  - ✓ Route Optimization of Multimodal Transportation Systems

Problem setting as a quantum computer

- Targeting sightseeing taxis in Kyoto, **optimization of the number of taxis dispatched** was studied.
  - ✓ The number of taxis required for 400 taxi trips is compared between the conventional method and quantum technology.
- **Route optimization was studied by formulating a multi-modal transportation system scenario under various conditions, such as different numbers of vehicles, different numbers of passengers, and different boarding and alighting places per vehicle,** which combines cars, shuttle buses, and taxis shown below.
  - ✓ Multiple cars will meet multiple guests at different locations and relay passengers to the turnoff where the shuttle bus will be waiting.
  - ✓ The shuttle bus takes the assembled passengers to another junction
  - ✓ picked up by a taxi from the junction and taken to various destinations
- Machine utilizes **D-wave Hybrid Solver Service**

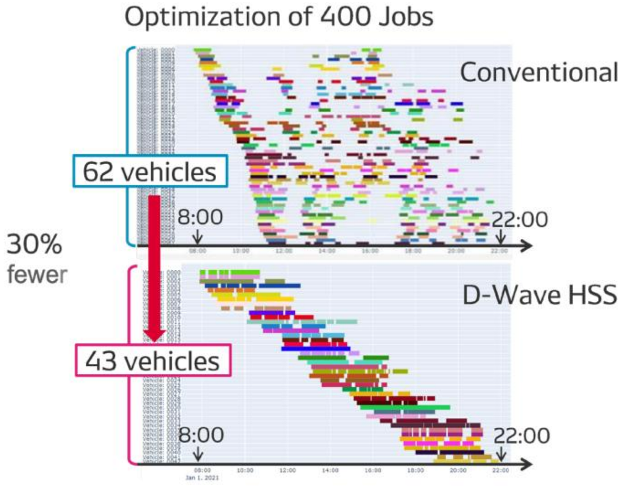
Reference: D-WAVE"DENSO: Optimizing Transportation with Quantum Computing" (https://www.dwavesys.com/media/f1hpibxr/denso-case-study2_v3.pdf)

Denso: Multimodal Transport System Route Optimization "2023" 2/2

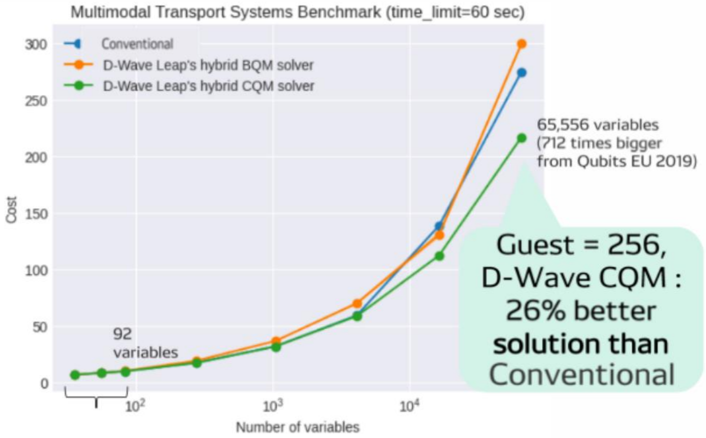
Expected business benefits

- **Comparing conventional methods with quantum technologies, we were able to reduce the number of taxis required to accommodate 400 trips by approximately 30%**
  - ✓ The previous requirement of 62 units was reduced to 43 units through the use of quantum technology
  - ✓ Optimization of the number of taxis **has the potential to significantly reduce CO2 emissions**

- For route optimization of a multimodal transportation system, a scenario with 256 passengers was **26% more efficient routing than conventional technology compared with quantum technology (D-wave CQM)**
  - ✓ The complexity of the scenario increased the computation time, but was able to **make the D-wave CQM solver more than 100 times faster on complex routing computations at the expense of 10% efficiency of the best solution**



optimization of the number of taxis



Route Optimization of Multimodal Transportation Systems

Reference: D-WAVE"DENSO: Optimizing Transportation with Quantum Computing" (https://www.dwavesys.com/media/f1hpibxr/denso-case-study2_v3.pdf)

Kyushu Electric Power and Sumitomo Corporation: Optimizing human flow for disaster damage control [2023/10]

Industry: Transportation
Process: Human Movement _ Land Transport
Method: combinatorial optimization

Background

- In recent years, with the increase in natural disasters and the aggravation of damage, **measures to prevent delay in evacuation** are required.
  - ✓ River flooding and flood disasters frequently occur due to heavy rain in various parts of Kyushu.
- Kyushu Electric Power has concluded comprehensive partnership agreements with local governments and financial institutions for **safe and secure community development** and dynamic and attractive community development, and is working to **resolve issues facing the Kyushu region and promote sustainable community development.**
  - ✓ **Evacuation support for local residents in the event of a disaster** is promoted as one of the measures.

Issues and motivation to be solved

- When evacuating in the event of a disaster, if individuals try to move as quickly as possible to reach an evacuation site, they may concentrate on a specific road and become in a dangerous situation. Therefore, **prompt evacuation instructions and guidance of evacuation routes are necessary.**
- **The problem with classical computers is that they take a lot of time to calculate,** he said, as there are so many options for evacuation routes to choose from.
- Since quantum technology is expected to efficiently solve optimization problems, this study **examines the application of quantum technology to calculate the optimal evacuation route for local residents by utilizing the knowledge of quantum technology accumulated by Sumitomo Corporation**

Problem setting as a quantum computer

- As the environment changes from moment to moment while residents are evacuating, the evacuation shelters allocated in advance are not always optimal, so **calculations to dynamically determine the evacuation route and evacuation destination for all local residents** are performed so that all residents can complete evacuation without delay.
- **To inform local residents of an optimal route to an evacuation center in consideration of traffic jams and accidents during evacuation and collapse of bridges during evacuation.**

Reference: Kyushu Electric Power Co., Inc. "Quantum Transformation by Sumitomo Corporation | Yusuke Okazaki," Q2B24 Tokyo (https://www.kyuden.co.jp/press_h231030b-1.html https://www.youtube.com/watch?v=Gqpj1R_9aGk)

OneSky, Tohoku University, Sumitomo Corporation (QX PJ): Traffic control for flying cars (air mobility)【2021/10】1/2

Industry	Transportation
Process	air transportation of people
Method	combinatorial optimization

Background

- **Air mobility is a next-generation means of transportation that is expected to reduce travel time in urban areas, improve the convenience of transportation on remote islands and in mountainous areas, and speed up emergency transportation and cargo transportation.**
- When the air mobility society is realized, it is assumed that many unmanned aerial vehicles (UAVs) will fly around, and **a system for real-time three-dimensional traffic control including UAVs will be necessary.**

Issues and motivation to be solved

- In order to ensure the safety and security of air traffic in the era of air mobility, it is necessary to **determine the most appropriate flight operation in light of ever-changing weather conditions, radio wave conditions, and other air mobility conditions.**
- But finding answers in real time from an exponentially growing pool of combinations can be **difficult with conventional computers.**
- For this reason, **OneSky, Tohoku University and Sumitomo Corporation (QX Project) have started a quantum technology demonstration to control a large number of air mobility in real time.**

Problem setting as a quantum computer

- **Comparison of conventional methods and quantum technologies regarding the number of air mobility devices that can be controlled in real time** was conducted.
- The machine uses **quantum annealing**

Reference: PR TIMES"Quantum computer improves traffic control for flying cars" (https://prtimes.jp/main/html/rd/p/000000005.000080581.html)

OneSky, Tohoku University, Sumitomo Corporation (QX PJ): Traffic control for flying cars (air mobility)【2021/10】2/2

Industry | Transportation
Process | air transportation of people
Method | combinatorial optimization

Expected business benefits

- The number of air mobility devices that can be controlled was **improved by approximately 70% over the conventional method.**
  - ✓ Up to now, the number was around 40, but increased to around 70 due to the use of quantum technology
- For one particular optimization problem, they achieved a **10 x speedup over a classical computer**

conventional method

use of quantum technology

Reference: PR TIMES"Quantum computer improves traffic control for flying cars" (https://prtimes.jp/main/html/rd/p/000000005.000080581.html)

ExxonMobil・IBM: Sea route optimization【2020/03】

Industry　Transportation

Process　Movement of goods _ Shipping

Method　combinatorial optimization

Background

- In 2021, more than 500 LNG carriers were used to transport critical fuel supplies by sea
  - ✓ It makes thousands of voyages a year to ports where LNG is deployed to power critical infrastructure.
- **Finding the optimal shipping route can be a complex optimization problem** and the location of each vessel **needs to be considered on each day of the year, along with the LNG requirements of each delivery location** in order to transport LNG efficiently
- Currently, **this kind of problem is difficult to compute on a classical computer.**
  - ✓ Even a simple problem involving dozens of ships can lead to **2 ^1 million combinations** of possible decisions

Issues and motivation to be solved

- **Quantum technology is expected to be used to find the optimal route for maritime transport, because it requires solving a problem with a large number of combinations, which is difficult with classical computers.**
- ExxonMobil and IBM **used quantum technologies to model offshore inventory routing, analyze the strengths and trade-offs of various vehicle and inventory routing strategies, and attempt to build a practical operational foundation.**

Problem setting as a quantum computer

- The route optimization problem to transport LGN efficiently is addressed.

IBM"ExxonMobil strives to solve complex energy challenges" (https://www.ibm.com/case-studies/exxonmobil)

ITOCHU Techno Solutions, TriValue, A-Star Quantum: Optimization of delivery planning【2025/6】1/2

Practical Application

Industry	Transportation
Process	Transportation of Goods _ Land Transport
Method	combinatorial optimization

Background

- In recent years, the importance of logistics has increased as an infrastructure that supports society, but there are a variety of issues
  - ✓ Driver shortage, traffic congestion, increased CO_2 emissions, etc.
- High-precision dispatch and route planning depend on trial and error by skilled personnel, resulting in a large workload and lead time. Due to the early closing of orders, the opportunity loss of vacant cars is also a problem.
- Combining CTC's transportation and delivery optimization know-how, TriValue's field expertise, and A-Star Quantum's quantum computation and mathematical optimization technologies, we jointly developed OptyLiner, aiming at high-speed automation of delivery plans and quality maintenance and improvement.

Issues and motivation to be solved

- Shorten the time required to create delivery plans and stably provide planning quality equal to or better than that of skilled workers
- Fine-tuning conditions and iterative simulations are performed in seconds to avoid early deadlines, reduce empty cars, and maintain service levels.

Problem setting as a quantum computer

- OptyLiner takes into account multiple factors, such as vehicle load and number of vehicles and driver working hours, and quickly calculates the optimal delivery route that minimizes travel distance, number of vehicles in operation and CO_2 emissions.
  - ➢ In the demonstration, OptyLiner completes route calculations in 5 seconds, compared to previous systems that took anywhere from a few minutes to over 20 minutes per calculation.

Reference: ITOCHU Techno Solutions Co., Ltd.: "Development of OptyLiner, which uses quantum computing and mathematical optimization to create delivery routes Demonstration reduced delivery planning time by approximately 95%" (https://www.ctc-g.co.jp/company/release/20250612-01921.html)

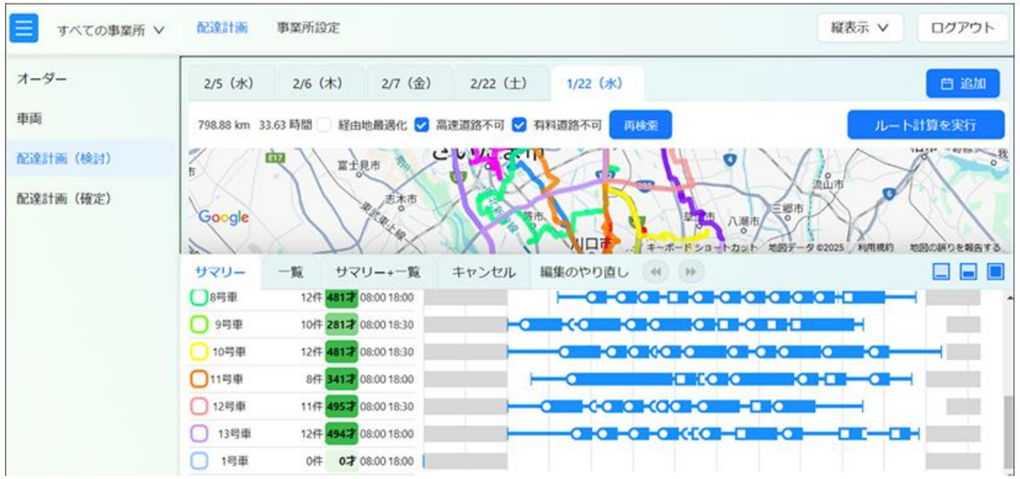
ITOCHU Techno Solutions, TriValue, A-Star Quantum: Optimization of delivery planning【2025/6】2/2

Practical Application

Industry	Transportation
Process	Transportation of Goods _ Land Transport
Method	combinatorial optimization

Expected business benefits

- Dramatic reduction in planning time (approx. 95%) and speedup of iterative review to push back order deadlines, expand order opportunities, and reduce vacancies
- Reducing operating costs, fuel costs and CO_2 emissions by reducing the number of vehicles in operation and shortening the total distance
- Standardize quality equivalent to or higher than that of skilled personnel, reduce personnel attributes and shorten training periods
- The price starts from 200,000 yen per month (excluding tax), and the target sales is 2 billion yen in 3 years.



Distribution planning image in OptyLiner

Reference: ITOCHU Techno Solutions Co., Ltd.: "Development of OptyLiner, which uses quantum computing and mathematical optimization to create delivery routes Demonstration reduced delivery planning time by approximately 95%" (https://www.ctc-g.co.jp/company/release/20250612-01921.html)

Quanmatic, Canes:
Delivery to multiple areas by sharing trucks among multiple stores【2025/12】1/2

Practical Application

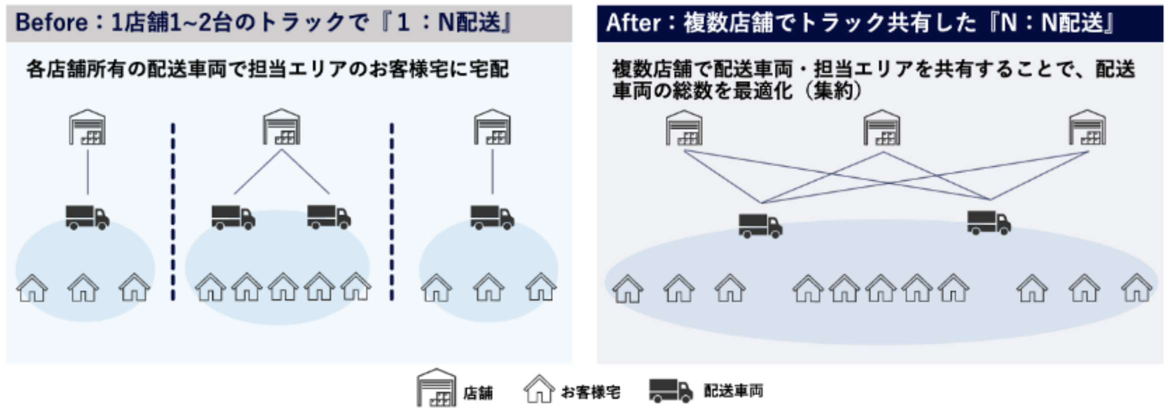
Industry	Transportation
Process	Transportation of Goods _ Land Transport
Method	combinatorial optimization

Background

- In recent years, the importance of logistics has increased as an infrastructure that supports society, but there are a variety of issues
  - ✓ Driver shortage, traffic congestion, increased CO2 emissions, etc.
- CAINZ Otaribin is a delivery service launched by CINZ in 2022. Its highly convenient system of delivering products purchased in stores to customers' homes within the same day at the earliest has been well received by customers. In 2024, the number of deliveries exceeded 20,000 a year.

Issues and motivation to be solved

- With the expansion of the CAINZ Ohappin service, delivery targets have been expanded to include stores with a small number of deliveries.
- In order to share trucks among multiple stores and deliver to multiple areas, **We would like to implement efficient delivery by designing flexible delivery routes.**
  - ➢ **Optimal delivery route calculation using quantum computation**



Real-time planning image of delivery route using quantum computing technology

Reference: QUANMATIC"Quanmatic brings quantum computing to CAINZ" (https://quanmatic.com/news/quanmatic-cainz-quantum-delivery/)

Quanmatic, Canes:
Delivery to multiple areas by sharing trucks among multiple stores【2025/12】2/2

Practical Application

Industry: Transportation

Process: Transportation of Goods _ Land Transport

Method: combinatorial optimization

Problem setting as a quantum computer

- **To address these complex computational challenges, Quanmatic and Canes have jointly developed a 'dynamic delivery system' with algorithms based on quantum computing technology.**
- Using algorithms based on quantum computing technology, **the optimal delivery route is planned in real time according to the demand of multiple stores**.

Expected business benefits

- As of November 2025, the introduction of this system in July 2025 **made it possible to optimize the required number of vehicles from 21 to 15 while maintaining service quality, and improved delivery efficiency by approximately 30%**.
- By adopting a joint delivery model in which vehicles are shared among multiple stores in the vicinity, it is possible to plan an optimal delivery route in real time according to the delivery demand of each store, thereby improving delivery efficiency.

Reference: QUANMATIC"Quanmatic brings quantum computing to CAINZ" (https://quanmatic.com/news/quanmatic-cainz-quantum-delivery/)

Q-CTRL, Network Rail: Railway scheduling optimization【2025/5】

Industry: Transportation
Process: Human Movement _ Land Transport
Method: combinatorial optimization

Background

- Through its extensive and complex operations, the rail industry faces a variety of challenges at every planning stage, from network design and train scheduling to crew management
- Significant obstacles must be overcome before quantum computing can realize its potential to outperform other approaches in complex optimization problems. Current quantum devices are vulnerable to environmental interference, leading to errors that limit the usefulness of today's quantum computing
- Introducing Fire Opal, error suppression performance management software allows users to get the most performance out of their current Quantum hardware

Issues and motivation to be solved

- To quickly calculate course setting and time adjustment of many trains in a short time in a form of zero contention and minimum delay under safety constraint.

Problem setting as a quantum computer

- By combining Q-CTRL's error suppression technology with problem-specific workflow development, coupled with ongoing exchanges with Network Rail to align problem formulations with real-world requirements, we have made significant progress in turning the promise of quantum computing into tangible benefits.
- Using the Fire Opal performance optimization platform, Q-CTRL runs a real scheduling problem on IBM quantum hardware, setting a new record as the largest constrained quantum optimization problem to date.
  - Calculated the exact route of 26 trains over a 18 minute period at London Bridge Station

Expected business benefits

- Optimizing scheduling by increasing the number of trains that can pass in the same time frame and reducing congestion in the station yard

See Also: Quantum Computing Report: "Q-CTRL and Network Rail Demonstrate Large-Scale Quantum Optimization for Rail Scheduling" (https://quantumcomputingreport.com/q-ctrl-and-network-rail-demonstrate-large-scale-quantum-optimization-for-rail-scheduling/); Q-CTRL: "Accelerating the schedule for quantum-enhanced rail" (https://q-ctrl.com/case-study/accelerating-the-schedule-for-quantum-enhanced-rail)

NEC, NEC Fielding: Optimization of maintenance parts delivery plan【2025/3】1/2

Practical Application

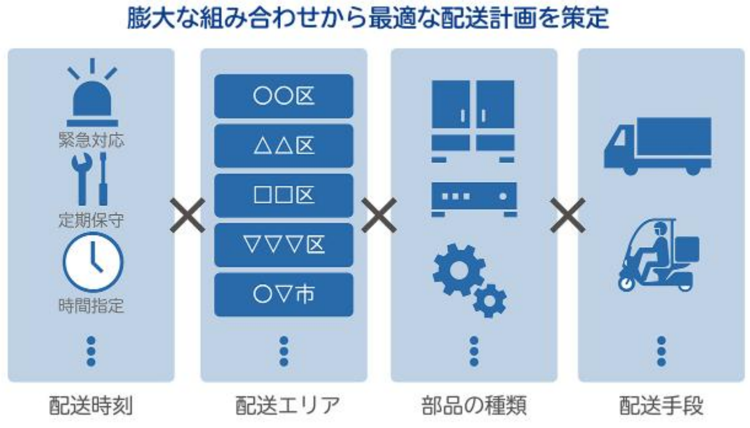
Industry	Transportation
Process	Transportation of Goods _ Land Transport
Method	combinatorial optimization

Background

- NEC Fielding's Tokyo Parts Center delivers maintenance parts to hundreds of locations in Tokyo's 23 wards 24 hours a day, 365 days a year.
- CE (Customer Engineer) who carries out maintenance and repair is moved by public transportation, and maintenance parts are sent separately by vehicle or motorcycle, assuming the operation peculiar to the urban area.
- Parking difficulties and traffic jams are common in urban areas, and it is essential to be punctual and optimize the stacking of multiple projects in accordance with the CE arrival time.
- Conventionally, a skilled person would spend two hours making a plan for the previous day using vast conditions and tacit knowledge.
- NEC Fielding built a production system using quantum-inspired technology (NEC's Vector Annealing: VA) and put it into operation in October 2022 with the aim of optimizing delivery for GX.

Issues and motivation to be solved

- We want to optimize logistics by developing high-quality plans in a short time under very large combinations and complex constraints.
- Eliminate the attribution of delivery planning that relied on expert knowledge and drastically reduce the time required to train successors



distribution plan optimization image

See: NEC: "Using Quantum-Inspired Technologies to Optimize Logistics " (https://jpn.nec.com/techrep/journal/g24/n01/240111.html)

NEC, NEC Fielding: Optimization of maintenance parts delivery plan【2025/3】2/2

Practical Application

<u>Industry</u> Transportation

<u>Process</u> Transportation of Goods _ Land Transport

<u>Method</u> combinatorial optimization

Problem setting as a quantum computer

- Uses VA (Vector Annealing), which utilizes quantum inspired technology developed to solve large-scale combinatorial optimization problems at high speed
    - High-speed solution processing is realized by performing optimization calculations on the supercomputer SX-Aurora TSUBASA (high-speed matrix calculation and high-speed memory access) developed by NEC.

Expected business benefits

- Approximately 2 hours of work was reduced to 12 minutes, and man-hours were reduced by shortening the time required to create a delivery plan.
- Improvement of planning quality through discovery of useful route plans that were not noticed in the past at the same level as experienced personnel

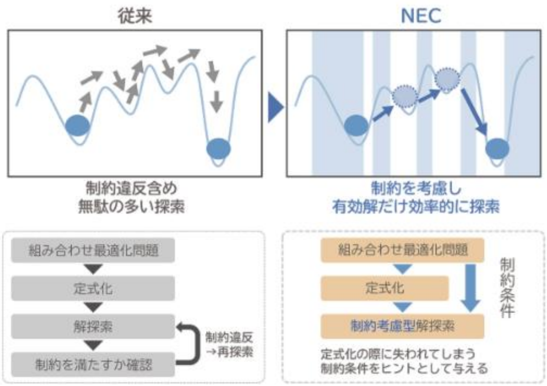


Image of Constraint-Aware Search Algorithm with VA

See: NEC: "Using Quantum-Inspired Technologies to Optimize Logistics " (https://jpn.nec.com/techrep/journal/g24/n01/240111.html)

Energy

Combinatorial Optimization	Optimization of Power Distribution Demand Planning	P129
	Optimizing facility operation plans to reduce power consumption at data centers	P131
	VPP supply-demand adjustment optimization using quantum GAN and QAOA	P133
	Optimization of resource allocation for electricity demand	P135
	Energy grid optimization	P137
AI	Estimation of unstable renewable power output	P138
Simulation	Nitrogen Fixation Reaction Simulation for Efficient Ammonia Synthesis	P140
	Optimization of power market transactions	P143

Chubu Electric Power: Optimization of Power Distribution Demand Planning【2021/07】1/2

Industry: Energy
Process: power generation
Method: combinatorial optimization

Background

- The distribution division of Chubu Electric Power Power Power Grid is engaged in **construction and maintenance of utility poles and wires to deliver electricity to customers' homes.**
- In the daily maintenance and operation work, the personnel in charge of operations at each sales office apply for the supply, suspension, and expansion of electricity from customers in their area, and when they receive information about a power outage due to a failure, they **go to the site to perform construction, inspection, and restoration work as necessary.**
- In the work plan (demand response plan), **the operation manager of the sales office prepares the schedule considering the daily work and the number of personnel.**

Issues and motivation to be solved

- The combination of visit order and job allocation is not always obvious, but it would be useful to automatically optimize **manual** scheduling
- When an unexpected event occurs during work (an emergency event leading to a power failure or an electric shock), **it is necessary to reschedule according to the situation** based on the work situation at each site and the position information of each person in charge of work.
- Since the number of possible combinations of work plans is enormous when constraints such as the order of patrolling the customer's house, the work skill of the person in charge of the work, the time period when the work can be done, and the travel time are taken into account, **in this demonstration, the effectiveness of Fujitsu's digital annealer is verified against an enormous number of combinatorial optimization problems**

Problem setting as a quantum computer

- Chubu Electric Power Power Power Grid **automatically created a work plan under the following objective function and constraint conditions using a part of the daily work results at 1 sales office (40 works extracted from electronic data) as test data**
  - ✓ As an objective function, only **reduction of business hours** was targeted.
  - ✓ **Limits are as follows:**
    - Each task is performed only once
    - Each worker cannot perform other tasks from start to completion
    - Each worker cannot perform other tasks while on the move
    - Some tasks have time to run
    - The first task is defined as coming to work, and each worker starts work at the specified time.
    - The last task is defined as returning to the office, and each worker returns to the office at some time and cannot execute the task thereafter.
- In addition, the following **incidental conditions of actual operation** are taken into account:
  - ✓ All SEs return to the office at 12:00 and have a break until 13:00
  - ✓ The travel time by car varies depending on the time of day.
  - ✓ Unexpected work may occur. Reschedule the demand plan from that point when it occurs
- The machine **utilizes Fujitsu digital annealer**

Reference: Fujitsu Limited, "Optimization of Power Distribution Demand Planning by Digital Annealer" (https://www.fujitsu.com/jp/about/resources/publications/technicalreview/topics/article010.html)

Chubu Electric Power: Optimization of Power Distribution Demand Planning【2021/07】2/2

Expected business benefits

- In the optimization verification of the demand response plan, **we compared the digital annealer with the classical commercial solver (Gurobi) and showed the effectiveness of the digital annealer in terms of solution time and work completion time** using test data.
- Regarding the solution time, **digital annealer is dominant in all patterns** in patterns (1), (2), (3), and (4) (refer to the figure on the right)
  - ✓ In pattern (1), **digital annealer** found a 17: 40 business completion solution, **whereas Gurobi did not find a valid optimal solution over time.**
  - ✓ Even in the case of pattern (3), the digital annealer was able to solve the problem in about 1.5 times more time than pattern (2), and **it was faster than Gurobi**.
- The effectiveness of the digital annealer was confirmed with regard to the work completion time.
  - ✓ With more than 5 workers, all jobs were completed at 17:00.
  - ✓ Although direct comparison with human system performance is not possible, **we confirmed the feasibility of efficient scheduling by digital annealer** and it was possible
    (There was a paper slip job that could not be reflected in the test data, and the work completion time by human systems was not measured under the same conditions.)

パターン	検証結果		
	業務完了時刻	デジタルアニーラ 求解時間（秒）	Gurobi Optimizer 求解時間（秒）
① 作業担当者数：4人	17:40	857	― (17:40の解得られず)
② 作業担当者数：5人	17:00	35	120
③ 作業担当者数：5人＋突発的な作業	17:00	35＋16※	120＋19※
④ 作業担当者数：6人	17:00	5	12

※＋の後の数値は，突発的な作業発生時の再計算に要した時間。

Reference: Fujitsu Limited, "Optimization of Power Distribution Demand Planning by Digital Annealer" (https://www.fujitsu.com/jp/about/resources/publications/technicalreview/topics/article010.html)

NRI: Optimizing facility operation plans to reduce power consumption at data centers 【2022/12】1/2

Industry: Energy
Process: Retailers and customers
Method: combinatorial optimization

Background

- NRI is conducting technical verification and research and development to clarify how quantum computing technology can be used to solve various social issues, including global environmental problems.
- **With the trend toward decarbonization and rising electricity prices, the reduction of electricity consumption is drawing attention.**
- NRI's business requires **highly power-efficient facility operation plans for data centers, which account for approximately 80% of electricity consumption**

Issues and motivation to be solved

- For the heat source facilities used for air conditioning and other operations at NRI's Tokyo Data Center 1, we conducted **Demonstration Tests for Optimal Operation Planning Using Quantum Computers** from April to September 2022 in order to create highly power-efficient facility operation plans
- This demonstration experiment was carried out **in collaboration with Ozeki Laboratory of Tohoku University** which is advancing the applied research of quantum computer.

Problem setting as a quantum computer

- **Analyzed data affecting power consumption at data center heat sources and built mathematical models** using a mathematical planning approach to formulating business challenges
- Using the constructed mathematical model, **the operation plan of the heat source facility that minimizes electric power consumption was calculated**.
  - ✓ As a precondition, **considering that the amount of cooling heat required in the data center will increase by 30% in the future** against the background that the equipment operated in the data center is increasing year by year
- The machine uses **D-wave Advantage, a quantum computer with quantum annealing.**
  - ✓ In order to perform the calculations on the quantum computer, the **Fixstars Amplify SDK from Fixstars Amplify** was used.

Reference: NRI"Nomura Research Institute conducts demonstration tests using quantum computers to reduce power consumption in data centers" (https://www.nri.com/jp/news/info/cc/lst/2022/1206_1)

NRI: Optimizing facility operation plans to reduce power consumption at data centers 【2022/12】2/2

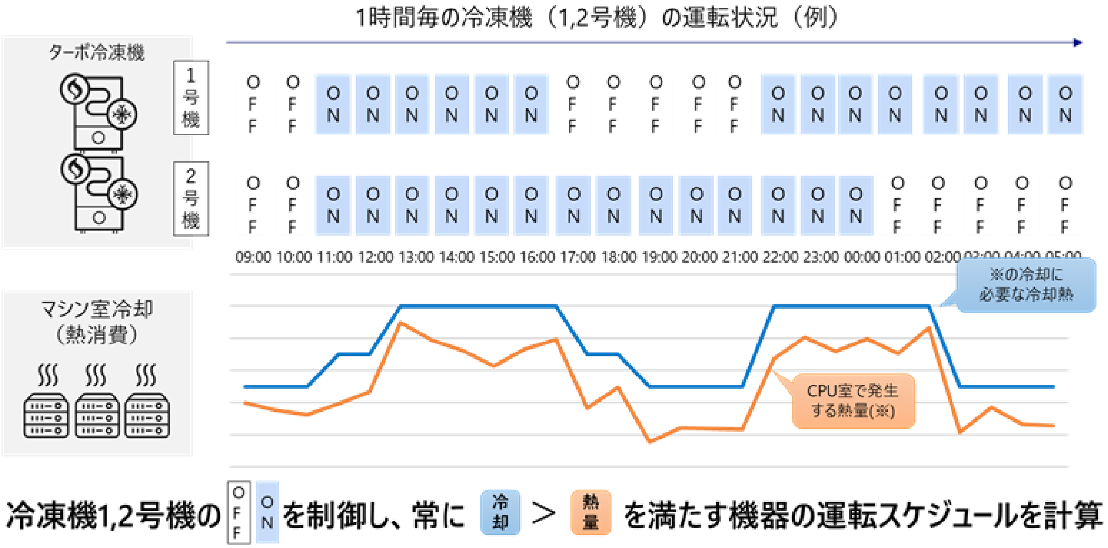
<u>Industry</u> Energy

<u>Process</u> Retailers and customers

<u>Method</u> combinatorial optimization

Expected business benefits

- If the heat source facilities are operated according to the operation plan, **electricity consumption is estimated to be reduced by up to 10%** in the spring and autumn seasons when the outside temperature is around 20 degrees Celsius.
- The mathematical model used for optimization in this demonstration experiment is not specific to NRI's data center and **can be applied to general building heat source equipment.**



Calculated operation plan image of the refrigerator in the heat source facility

Reference: NRI"Nomura Research Institute conducts demonstration tests using quantum computers to reduce power consumption in data centers" (https://www.nri.com/jp/news/info/cc/lst/2022/1206_1)

Grid: VPP supply-demand adjustment optimization using quantum GAN and QAOA [2024/9] 1/2

Industry	Energy
Process	Power transmission and distribution, input
Method	AI

Background

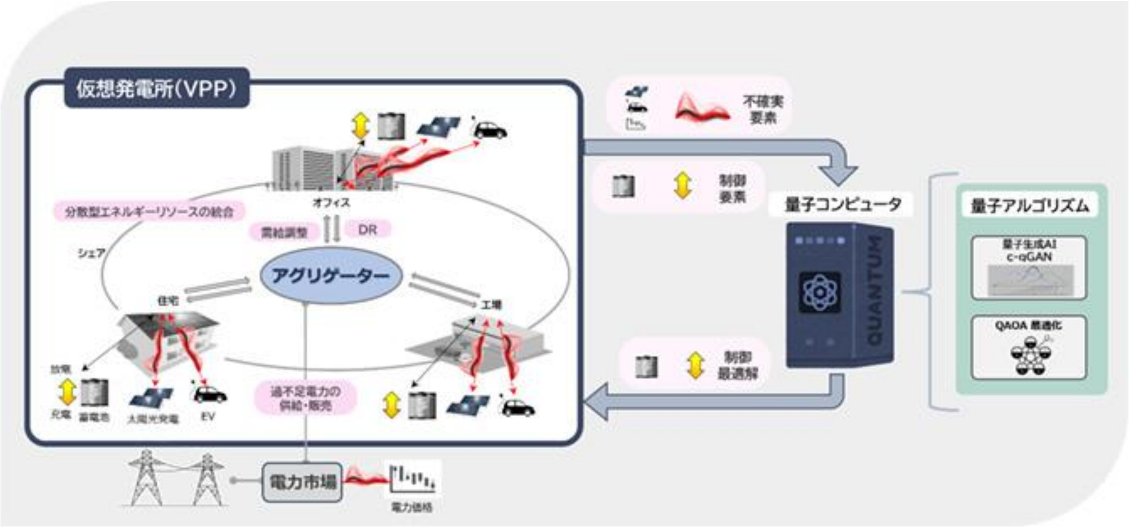
- As the introduction of renewable energy advances worldwide, the instability of electricity supply due to renewable energy, which is easily affected by weather, has become an issue.
- Virtual power plants (VPPs) are attracting attention as a solution. They treat small power plants such as offices and storage batteries as a single power plant, and use electricity without waste by managing and adjusting them in cooperation with the electricity market. **Supply and demand adjustment, which optimizes the balance between power generation and consumption in real time, plays an important role in realizing efficient and stable power supply,** based on DR (demand response) from each facility.

Issues and motivation to be solved

- Stochastic programming, which is currently used to create scenarios for supply-demand adjustment of VPPs, evaluates the risks and returns of a plan by sampling scenarios that may occur many times within a range of distributions. However, **it is difficult to put it into practical use because of the enormous computational complexity, and it has not been effective in actual supply-demand management.**
- **There has not been enough research on how to solve the highly uncertain power system problems computationally with quantum computers.**

Expected business benefits

- This initiative will be developed in three stages: (1) optimizing supply and demand adjustment of VPP for one household, (2) applying it to several households, and (3) supporting more than 100 households.
- Based on predictions that a quantum computer with error correction (FTQC) functions will be put into practical use around 2035, **we have been conducting research with an eye toward implementation for social problems since 2024.**



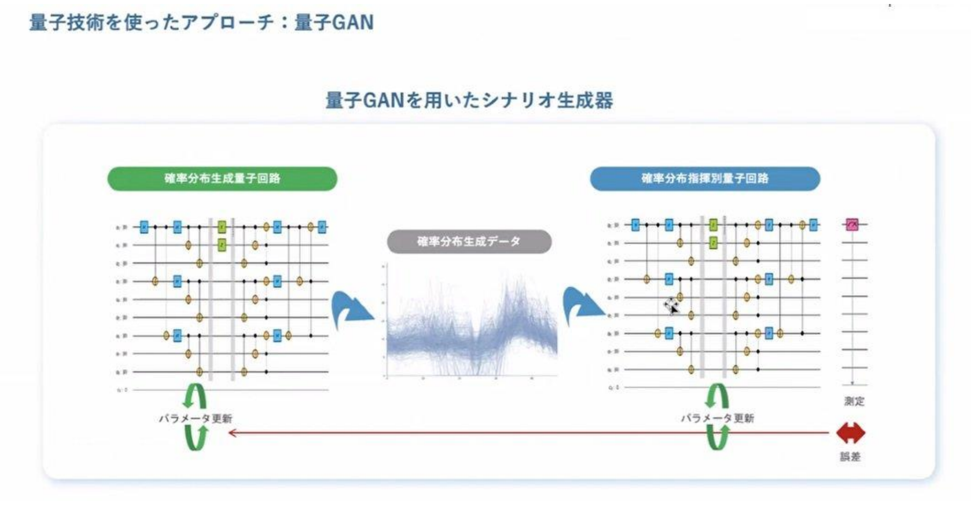
Realization of VPP Supply and Demand Adjustment Optimization Method

Reference: MONOist, "Optimizing supply and demand adjustment of a virtual power plant using a quantum computer" (https://monoist.itmedia.co.jp/mn/articles/2409/12/news071.html), The University of Electro-Communications, "Report: Selected as a project for cyber-physical development of quantum-classical hybrid technology invited by the New Energy and Industrial Technology Development Organization (NEDO)" (https://www.uec.ac.jp/news/announcement/2024/20240910_6472.html)

Grid: VPP supply-demand adjustment optimization using quantum GAN and QAOA [2024/9] 2/2

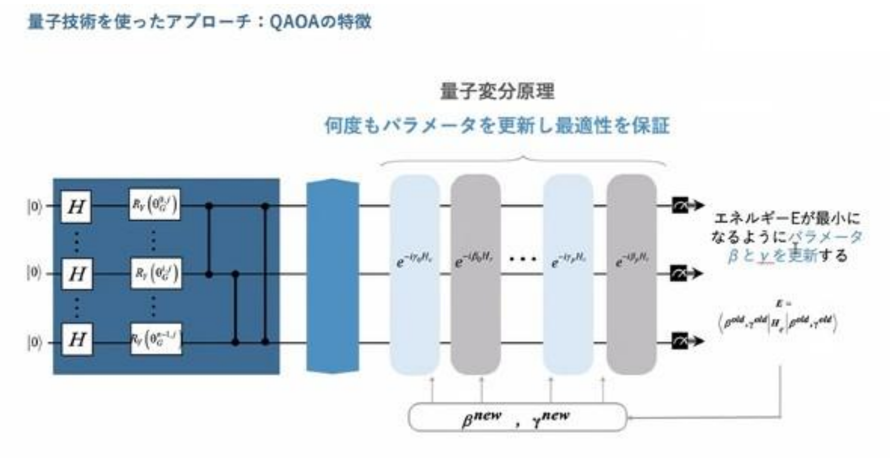
Problem setting as a quantum computer

- Research and development of a quantum classical stochastic optimization method utilizing gate type quantum technology for the purpose of eliminating and optimizing supply and demand uncertainty in VPP
- Specifically, we will conduct three studies: (1) mapping VPP uncertainties to quantum GAN *1; (2) solving VPP problems using quantum approximation optimization algorithms (QAOA *2 and); and (3) fusion of quantum GAN and QAOA.
- HW utilizes gated quantum technology



quantum GAN

*1 GAN is a network that enables the generation of data close to the real thing by learning while competing with Discriminator and Generator alternately. The classical GAN has the disadvantage that it is not good at generating discrete values due to the vanishing gradient problem.



QAQA

*(2) QAOA is called quantum approximation optimization algorithm and is an algorithm for solving combinatorial optimization problems using the quantum gate method.

Reference: MONOist "Optimizing supply and demand adjustment of a virtual power plant with a quantum computer" (https://monoist.itmedia.co.jp/mn/articles/2409/12/news071.html)

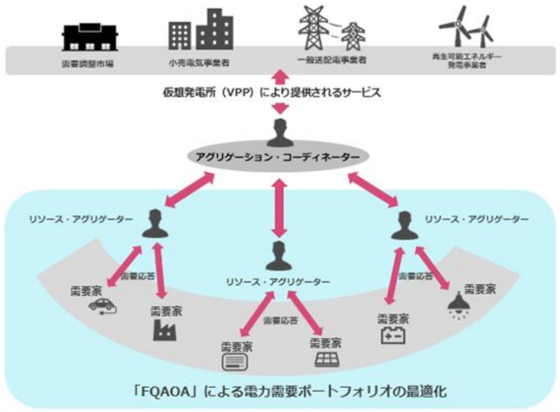
TIS, The University of Osaka: Optimization of resource allocation for electricity demand (2025/5) 1/2

Background

- The proliferation of renewable energy is leading to a shift from the traditional centralized supply of large power plants to a model that **leverages distributed energy resources.**
- Resource aggregation business, in which distributed resources are bundled to adjust supply and demand, is attracting attention. In this field, two entities, **aggregation coordinators** that optimize the supply and demand balance and **resource aggregators** that supply the desired amount of electricity through demand suppression, play important roles by constructing virtual power plants (VPP).
- Resource aggregators **need to achieve stable power procurement even in highly volatile environments by appropriately combining demand suppression amounts provided by multiple customers.**
- **The introduction of quantum optimization algorithms is expected to play an important role in power demand portfolio optimization** in the resource aggregation business.

Issues and motivation to be solved

- In the resource aggregation business, both securing procurement volume and stability are required.
- The problem is that conventional quantum optimization algorithms have difficulty in satisfying procurement plans due to limitations in calculation accuracy, and there is a discrepancy between the actual demand suppression amount and the expected electricity amount.



Power Demand Portfolio Optimization Image

See Also: TIS: "TIS and the Quantum Information and Quantum Life Research Center at The University of Osaka Develop a New Quantum Algorithm "FQAOA" ~ Achieved an approximately 10 fold increase in calculation accuracy for optimizing resource allocation in relation to electricity demand as a first step toward reducing environmental impact ~" (https://www.tis.co.jp/news/2025/tis_news/20250507_1.html)

TIS, The University of Osaka:
Optimization of resource allocation for electricity demand (2025/5) 2/2

<u>Industry</u> Energy

<u>Process</u> transmission and distribution

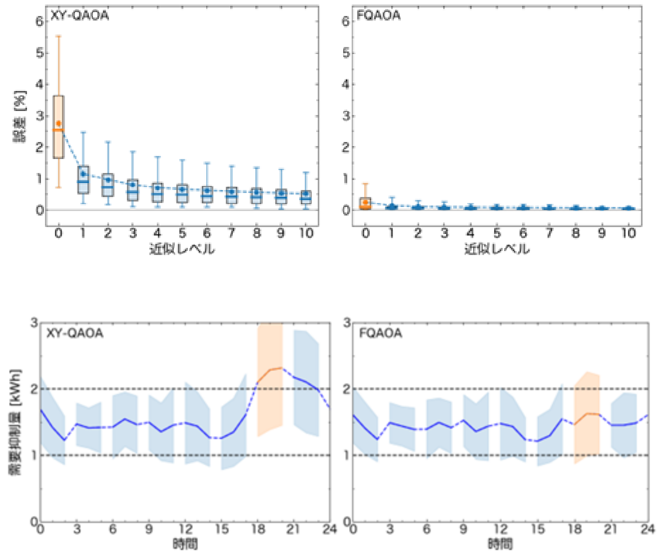
<u>Method</u> combinatorial optimization

Problem setting as a quantum computer

- TIS and The University of Osaka improved the jointly developed algorithm "FQAOA" and applied it to a power demand portfolio optimization problem.
- By adopting a new optimization approach that properly takes into account the balance conditions for aggregating the demand suppression amount that matches the desired procurement amount, **FQAOA** achieves a significant improvement in calculation accuracy compared to the conventional method.
  - With the conventional method, the error from the optimal solution was 27.6%, but by introducing "FQAOA," the error was reduced to 2.5%.
  - When the desired amount of electricity to be procured is set to 1 kWh to 2 kWh for all time zones, the calculation result shows that the amount of electricity obtained by the conventional method is 2.23±0.858 kWh for the time zone between 18:00 and 21:00, whereas the amount obtained by using "FQAOA" is 1.57±0.604 kWh, which makes it possible to procure electricity with higher accuracy.

Expected business benefits

- Quantum optimization algorithms **are expected to be applied not only to improve energy efficiency but also to reduce environmental impact** in the energy field.



Comparison of Results between Conventional Calculation and "FQAOA"

See Also: TIS: "TIS and the Quantum Information and Quantum Life Research Center at The University of Osaka Develop a New Quantum Algorithm "FQAOA" ~ Achieved an approximately 10 fold increase in calculation accuracy for optimizing resource allocation in relation to electricity demand as a first step toward reducing environmental impact ~" (https://www.tis.co.jp/news/2025/tis_news/20250507_1.html)

IonQ, Oak Ridge National Laboratory (ORNL), US Department of Energy (DOE) : Energy grid optimization [2025/7]

Industry	Energy
Process	transmission and distribution
Method	combinatorial optimization

Background

- Currently, more than 60% of the energy used to generate electricity is lost, and improved planning and calculation methods are expected to reduce waste.
- Due to the modernization of the electric power grid, it is essential to consider both dispatchable power sources such as nuclear power, thermal power, and hydropower and variable power sources such as solar power and wind power at the same time, and the generator schedule (unit commitment) complexity increases.

Issues and motivation to be solved

- We want to solve large-scale unit commitments that minimize total costs while meeting demand and reserve capacity in high-quality and realistic time under variable renewable energy and complex operational constraints.

Problem setting as a quantum computer

- Demonstration of a hybrid method that combines IonQ's 36 qubit Forte Enterprise with classical computing to address realistic unit commitments (26 machines x 24 periods)

Expected business benefits

- The possibility of solving the unit commitment problem of power grids using ion trap quantum computing devices is demonstrated.
- The quantum optimization method is applicable not only to energy but also to a wide range of industries including logistics, scheduling, and finance.

See Also: IONQ: "IonQ Partners with Oak Ridge National Laboratory, Demonstrating Quantum Power Grid Optimization Advances" (https://investors.ionq.com/news/news-details/2025/IonQ-Partners-with-Oak-Ridge-National-Laboratory-Demonstrating-Quantum-Power-Grid-Optimization-Advancements/default.aspx)

EDF (French power company): Estimation of unstable renewable power output [2023/10] 1/2

Industry	Energy
Process	power generation
Method	AI

Background

- Renewable energy sources that extract energy from the natural environment, such as solar and wind power, offer great potential for decarbonization to combat climate change, but **the output of renewable energy sources is unstable.**
  - ✓ Unlike other energy sources, which can be turned on and off as energy consumption changes, **the management of renewable energy sources needs to be fully optimized to meet demand** for grid stabilization.
- Thus, **there is a need to establish models to predict power output from unstable renewable sources.**
  - ✓ Unreliable forecasting models would require energy suppliers to use sources such as fossil fuels and other non-sustainable alternatives, which would add significantly to the environmental burden

Issues and motivation to be solved

- **Predictive models for renewable power output, which exhibit unstable and complex behavior, can be difficult to train and require large amounts of energy and data**
  - ✓ Predictive simulations rely on chaotic and difficult-to-model weather and climate conditions, requiring high-performance computing resources such as HPC
- **PASQAL, in collaboration with EDF, a French power company, has developed a model that uses quantum computer technology to reduce CO2 emissions in power prediction simulations and achieve high-precision power prediction.**
- In addition, after winning the 2023 PASQAL hackathon on sustainable solutions using quantum computers, the company plans to work toward demonstration.

Problem setting as a quantum computer

- **Models complex physical systems, such as renewable power sources, and compares the accuracy of classical and quantum computer models**
  - ✓ A **14 qubit emulator (assumed to be a gate)** was used as the quantum computer.
- We also conducted **a comparison of CO2 emissions using a classical computer and a quantum computer as a benchmark for energy consumption**
  - ✓ The quantum computer used was **Fresnel (gate), PASQAL's current commercial device.**

Reference: pasqal"Three Winning Quantum Projects Announced for the Blaise Pascal [re] Generative Quantum Challenge" (https://www.pasqal.com/news/winners-of-the-blaise-pascal-regenerative-quantum-challenge/), RTE"Le transport d'électricité, comment ça fonctionne?" (https://www.rte-france.com/wiki-energie/transport-electricite-comment-ca-fonctionne), Pasqal "The Blaise Pascal [re] Generative Quantum Challenge" (https://www.pasqal.com/news/the-blaise-pascal-regenerative-quantum-challenge-the-journey-winning-projects-and-lessons-drawn/), Microsoft PASQAL Provider (https://learn.microsoft.com/ja-jp/azure/quantum/provider-pasqal#fresnel1)

EDF (French power company): Estimation of unstable renewable power output [2023/10] 2/2

Industry	Energy
Process	power generation
Method	AI

Expected business benefits

- **High prediction accuracy exceeding that of classical reservoir based on neural network using classical computer with small data size**
- **When the data size is large, the quantum computer emits less CO2.**
  - ✓ Classical computers consume more energy as data size increases, but **quantum computers have constant CO2 emissions.**
  - ✓ **Around 105~106 for industrial use on the dataset, quantum computers emit less CO2 than classical computers.**

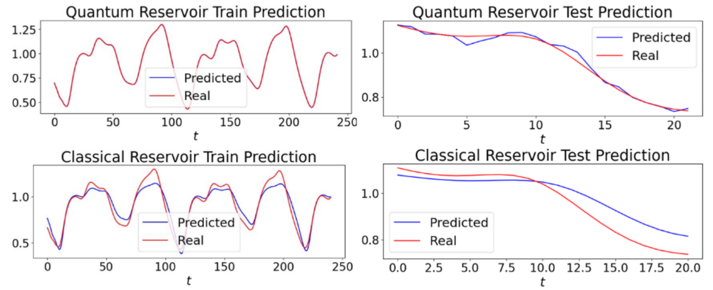


Figure 7.

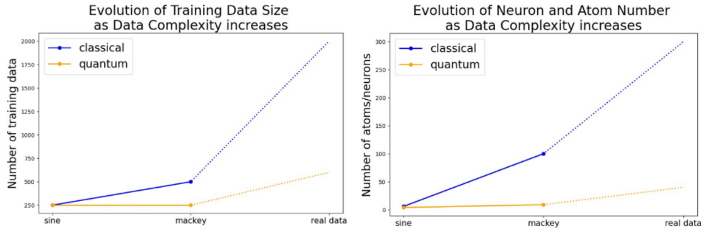
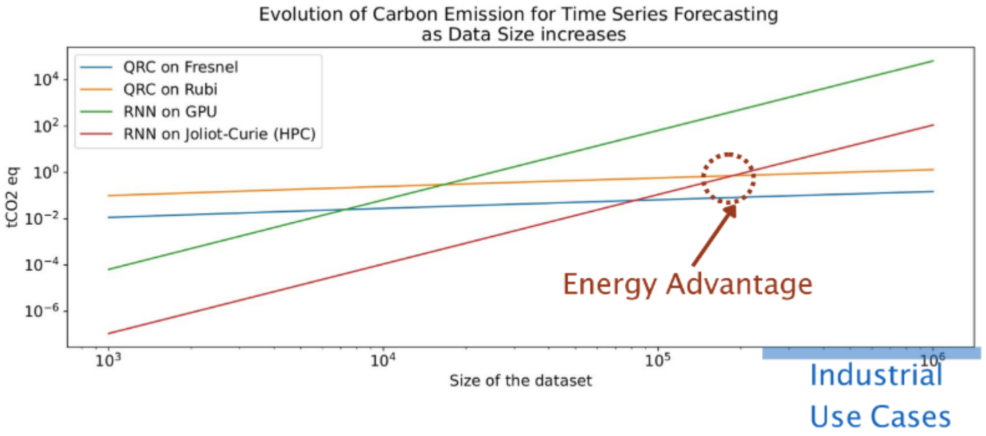


Figure 8.



ETH Zurich, Microsoft Research:
Nitrogen Fixation Reaction Simulation for Efficient Ammonia Synthesis【2017/07】1/3

Industry: Energy
Process: fuel synthesis
Method: Simulation

Background

- Ammonia is attracting **attention as a clean fuel alternative to fossil fuels** in global efforts to combat climate change
  - ✓ Contributing to decarbonization by not emitting CO2 during combustion
- On the other hand, **the way ammonia is made consumes a lot of energy and emits CO2.**
  - ✓ The **Haberbosch process,** which is currently the mainstream manufacturing method, is a synthesis method under high-temperature and high-pressure conditions (high temperature of 400~600°C and high pressure of 100~300 atm).
  - ✓ **It uses 1~2% of the energy consumed by the entire earth, and the amount of CO2 emitted during manufacturing also accounts for 1~3% of human emissions.**
- There is a need for an alternative, environmentally friendly, low energy consumption, low CO2 emission, ammonia production method to replace the "Haberbosch process"

Issues and motivation to be solved

- In the Haberbosch process, **most of the energy is consumed in the process of fixing nitrogen in the air,** but in nature, in particular, **in biological systems, nitrogen-fixing enzymes (nitrogenase) present in the roots of leguminous plants stimulate ammonia synthesis at normal temperature and pressure.**
  - ✓ The mechanism involves **a cofactor called FeMoco,** * and

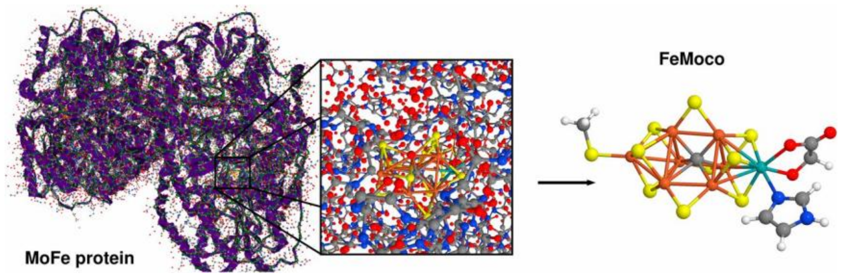
    *Chemicals other than proteins necessary for the catalytic activity of enzymes
- **The chemical reactions involving FeMoco are complex and quantum, making them difficult to simulate on a classical computer (supercomputer),** he said.
  - ✓ **The FeMoco cofactor in the nitrogenase enzyme is involved in ammonia synthesis as a transition metal catalyst,** but **the electron-electron interaction is strong**, and **the Hartree-Fock and DFT approximations do not capture the exact chemical reactions** that are commonly used in classical computers.
- Molecular simulations using quantum acceleration algorithms for quantum chemical calculations are currently being studied on quantum computers.

Reference: The University of Tokyo "World's First Synthesis of Ammonia from Nitrogen Gas and Water — World's Highest Catalytic Activity at Normal Temperature and Pressure, Toward a Sustainable Society —" (https://www.t.u-tokyo.ac.jp/hubfs/shared-old/press/data/setnws_20190425105724638383038O_077019.pdf) and National Institute of Science and Technology Policy "Interview with Mr. Keisuke Fujii, Professor, Department of Electronics and Optical Science, Graduate School of Basic Engineering, The University of Osaka: Leading the field of quantum information science in research and development of quantum software to realize universal quantum computer" (https://www.nistep.go.jp/activities/sti-horizon%E8%AA%8C/vol-07no-04/stih00273)

ETH Zurich, Microsoft Research:
Nitrogen Fixation Reaction Simulation for Efficient Ammonia Synthesis【2017/07】2/3

Problem setting as a quantum computer

- **Taking into account the electron correlation**, combining the density matrix renormalization group and the CASSCF (multi-configuration self-consistent field) method, which allows calculations involving a larger number of orbitals, **performing quantum computer calculations using quantum phase estimation**, performed.
- **As a quantum computer, it calculates under two conditions.**
  - ✓ **FTQC computable error rate achievable in the short to medium term, 10-3, Gate speed 100 ns**
  - ✓ **Future achievable FTQC computable error rates, 10-6, Gate speed 10 ns**



The iron-molybdenum cofactor (FeMoco) at the active center of the nitrogenase enzyme (left panel) causes the conversion of nitrogen gas to ammonia (right panel).

Reference: PNAS"Elucidating Reaction Mechanisms on Quantum Computers"(https://www.pnas.org/doi/10.1073/pnas. 1619152114)

ETH Zurich, Microsoft Research:
Nitrogen Fixation Reaction Simulation for Efficient Ammonia Synthesis【2017/07】3/3

Industry	Energy
Process	fuel synthesis
Method	Simulation

Expected business benefits

- **Due to the complexity and strong quantum nature of the chemical reactions involved in FeMoco, which are difficult to calculate with a classical computer, we** calculated **the computational resources and time required to simulate two conditions with a quantum computer.**
  - ✓ In order to keep the tolerance within 0.1 mHartree *1 of the exact solution, it takes more than 3 years with 111 logical qubits for both Structure1 and Structure 2 in Serial (single thread).
  - ✓ On the other hand, in PAR (multi-threaded), both are executed in 1.5 to 3 months at around 2000 logical qubits.
- showed that **quantum computers can be used to understand reaction mechanisms in complex chemical systems, taking as an example the unsolved problem of biological nitrogen fixation in nitrogen genase**

Table 1. Simulation time estimates

Structure	T gates	Cl. gates	Δt (10 ns)	Δt (100 ns)	Qubits
Quantitatively accurate simulation (0.1 mHa)					
Structure 1					
Serial	1.1×10^{15}	1.7×10^{15}	130 d	3.6 y	111
Nesting	3.5×10^{15}	5.7×10^{15}	15 d	4.9 mo	135
PAR	3.1×10^{16}	3.1×10^{16}	110 h	1.5 mo	1,982
Structure 2					
Serial	2.0×10^{15}	3.1×10^{15}	240 d	6.6 y	117
Nesting	6.5×10^{15}	1.0×10^{16}	27 d	8.9 mo	142
PAR	6.0×10^{16}	6.0×10^{16}	210 h	2.9 mo	2,024
Qualitatively accurate simulation (1 mHa)					
Structure 1					
Serial	1.0×10^{14}	1.6×10^{14}	12 d	3.9 mo	111
Nesting	3.3×10^{14}	5.6×10^{14}	1.4 d	14 d	135
PAR	3.0×10^{15}	3.0×10^{15}	11 h	4.6 d	1,982
Structure 2					
Serial	1.9×10^{14}	3.0×10^{14}	22 d	7.2 mo	117
Nesting	6.0×10^{14}	9.9×10^{14}	2.5 d	25 d	142
PAR	5.5×10^{15}	5.5×10^{15}	20 h	8.3 d	2,024

Listed are the number of Clifford and T-gate operations, the estimate of the run time (Δt), and the number of logical qubits required to obtain energies within 0.1 mHa or 1 mHa for two different structures of FeMoco on a quantum computer. Structure 1 is for spin state $S = 0$ and charge $+3$ elementary charges with 54 electrons in 54 spatial orbitals. Structure 2 is for spin state $S = 1/2$ and charge 0 with 65 electrons in 57 spatial orbitals (see *SI Appendix* for further details). These run times and gate counts are likely to be pessimistic.

Reference: PNAS"Elucidating Reaction Mechanisms on Quantum Computers"(https://www.pnas.org/doi/10.1073/pnas. 1619152114)

Optimization of power market transactions [2024/7] 1/2

technical area	Energy
Process	power generation
Method	Simulation

Background

- Electricity markets have been liberalized in many countries, moving **from a monopolistic utility operation to a market where many power producers and energy traders compete**
- Volatility in the electricity market has also increased due to the unstable introduction of renewable energy and the expansion of distributed energy. There is a growing need for **optimization of bidding strategies and decision-making by electricity market participants (power producers).**

Issues and motivation to be solved

- Traditional Multi-Agent Reinforcement Learning (MARL) Techniques Can Model Power Generation Company (GENCO) Decisions
- On the other hand, **uncertainty due to policies and long-term business plans, the state of assets, traders' risk appetite and (un) rationality**, GENCO has not reached optimal decision-making. Also, because GENCO cannot observe some market information, it **cannot accurately predict market transaction results**. In addition, the compensation of each GENCO is affected by the decisions of other GENCOs that compete.
- This calls for **optimizing electricity market transactions** using quantum computers. There is a growing need to more accurately simulate the equilibrium and dynamics of the electricity market by modifying conventional MARL to quantum MARL.

Problem setting as a quantum computer

- **Optimize bidding strategies and maximize returns in the electricity market** by power generation companies (GENCO)
- The specific machine isn't specified, but it uses a **gated quantum computer.**
- **Quantum Multi-Agent Deep Q-Network Algorithm (Q-MADQN)** for Simulating Electricity Market Bidding
  - ✓ This method integrates variational quantum circuits into a multi-agent reinforcement learning (MARL) framework to effectively evaluate and simulate uncertainties in the electricity market.

Reference: arXiv"Evaluating Uncertainties in Electricity Markets via Machine Learning and Quantum Computing" (https://arxiv.org/pdf/2407.16404)

Optimization of power market transactions [2024/7] 2/2

Industry	Energy
Process	power generation
Method	Simulation

Expected business benefits

- (6) We conducted bidding strategy studies for electricity market transactions using Q-MADQN and conventional MADQN models respectively, utilizing data from three GENCOs (power generation companies) (power generation costs, etc.), and compared the results.
- As a result, Q-MADQN was able to explore potential actions and explore potential actions that could not be detected by conventional MADQN, and **confirmed that the total profit of GENCO increased significantly by utilizing Q-MADQN**

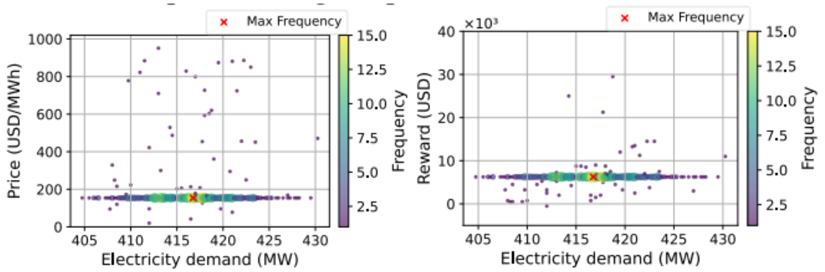


Fig. 2. State-action and reward distributions of GENCO 5 using MADQN.

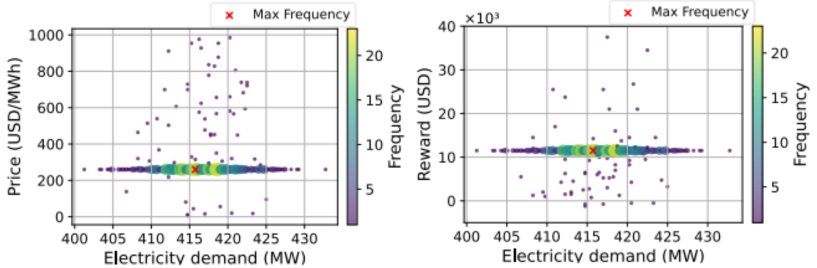


Fig. 3. State-action and reward distributions of GENCO 5 using Q-MADQN.

Reference: arXiv"Evaluating Uncertainties in Electricity Markets via Machine Learning and Quantum Computing" (https://arxiv.org/pdf/2407.16404)

Other

Combinatorial Optimization	Optimization of radio base station settings	P146
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	Image Generation Using Quantum Neural Networks	P160
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Simulation	Prevention of Resonance by Natural Frequency Analysis Using Quantum Phase Estimation	P167
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SoftBank: Optimization of radio base station settings [2025/7]

Industry	Other
Process	Other
Method	combinatorial optimization

Background

- Carrier Aggregation (CA) is a technology that realizes high-speed and stable communications by simultaneously using radio waves of multiple frequency bands, and it is necessary to establish the association between base stations (hereinafter, “CA link ”) in advance.
- However, due to the increase in the number of base stations, the configuration of CA links has become dramatically more complex.
  - For example, there are 45 possible combinations of 2 stations from 10 stations, and each combination has the option of "set or not set CA link," resulting in a total of 35 trillion combinations (2 to the power of 45).
  - In addition, limitations such as the maximum number of CA links that can be configured per base station make it extremely difficult to find the optimal combination that maximizes CA coverage.

Issues and motivation to be solved

- Because of limitations such as the maximum number of CA links that can be configured per base station, it is extremely difficult to find the optimal combination that maximizes the CA's available area.
- a computer specialized in combinatorial optimization problems that finds an optimal solution by searching for a state that minimizes energy

Problem setting as a quantum computer

- The distribution of areas where carrier aggregation (a method of increasing communication speed by bundling multiple frequency bands) is available is expressed by a mathematical model based on radio wave conditions from multiple base stations, and the optimum setting is calculated in a short time using mathematical optimization.

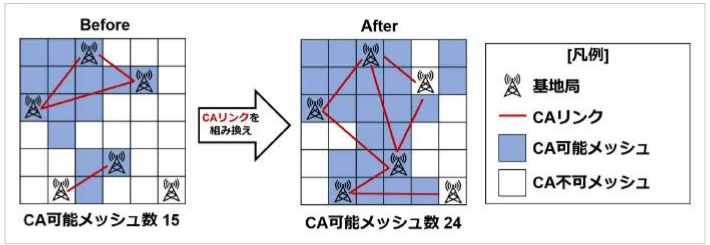


図1. CA可能メッシュ数を最大化するようにCAリンク構成を最適化

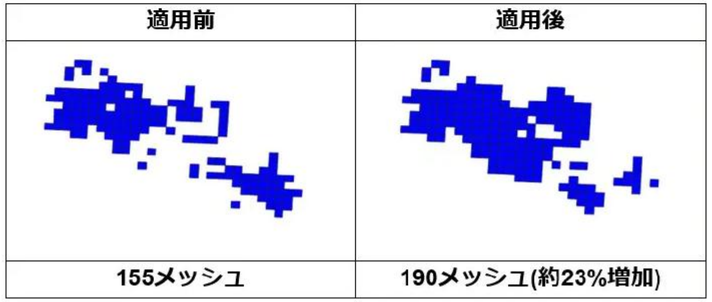


図2. 最適化前後のCA可能エリアの一例（青いメッシュ部分がCA使用可能エリア）

Optimization of base station and CA link combination

Expected business benefits

- As a result of testing in Tokyo area, downlink data communication speed using carrier aggregation improved by about 10% and data communication volume increased by up to 50%.
- Demonstration of significant improvement in communication quality with only existing equipment
- They are classified into classical type, quantum type, and quantum inspired type, and are expected to be applied in various fields such as logistics and finance.

Reference: SoftBank "Optimizing Wireless Base Station Settings to Improve Communication Performance Using Quantum Computing Technology" (https://www.softbank.jp/corp/news/press/sbkk/2025/20250729_01/)

Takenaka Corporation:
Improving the efficiency of educational facility development plans [2025/2] 1/2

Industry	Other
Process	Other
Method	combinatorial optimization

Background

- In order to increase the operation rate of classrooms and other facilities in educational facilities and improve management efficiency, it is necessary to develop an optimal facility development plan for the building in accordance with the curriculum implementation plan.

Issues and motivation to be solved

- A curriculum plan for an educational institution needs to consider multiple factors, such as the structure of the institution, the number of teachers, and the number of students. **In the case of a large university, a period of several months is needed to create one plan,** where more than 500 classes are held throughout 1 semester.

Problem setting as a quantum computer

Formulate an optimal educational facility development plan according to the following procedures

1. Identify the current status of educational facilities and curricular implementation constraints
2. Obtain the following data from educational institutions
    1. Teachers' information such as available lecture times
    2. Information on class names and lesson plans of subject faculties
    3. Information about the facility, such as the number of classrooms and capacity
3. devise a plan for the structure of facilities in terms of the number of classrooms and capacity
4. Organize and convert the data obtained from educational facilities and the proposed facility structure data set in our company into a format that can be read by the program.
5. Modify and test the program to calculate the optimal facility structure to accommodate the specific constraints of educational facilities
6. Run the program to calculate the optimal facility configuration
7. Check the calculated results with the educational institution and receive feedback to revise and re-execute the program.
8. draw up a facility development plan based on the final facility structure plan

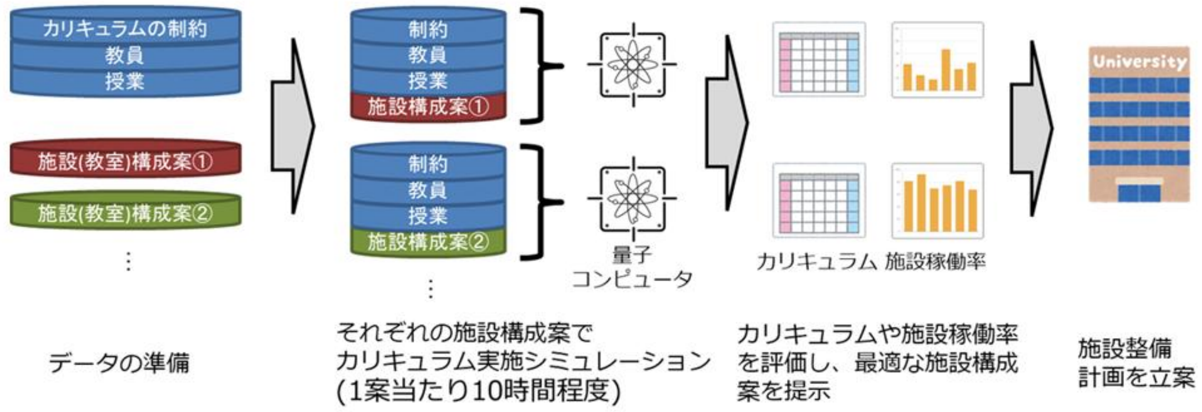
Reference: Takenaka Corp. "Development of optimization technology for educational facility development plan using quantum computer" (https://www.takenaka.co.jp/news/2025/02/04/)

Takenaka Corporation:
Improving the efficiency of educational facility development plans [2025/2] 2/2

Industry	Other
Process	Other
Method	combinatorial optimization

Expected business benefits

- Confirmation of restrictions on curriculum implementation, preparation of data necessary for simulation, and arrangement of program preparation require the same amount of time as the conventional method. However, once the preparation is complete, it becomes possible to create (simulate) 1 curriculum proposal in about 10 hours, and **it becomes possible to simulate multiple curriculum implementation proposals in a short time by changing conditions such as facility configuration.**
- It is possible to evaluate multiple curriculum implementation plans obtained through simulation and propose an optimal facility development plan based on the results.



Design image of educational facility development plan

Reference: Takenaka Corp. "Development of optimization technology for educational facility development plan using quantum computer" (https://www.takenaka.co.jp/news/2025/02/04/)

Google:
Using quantum data to predict the properties of physical systems with higher accuracy [2022/6] 1/3

Industry: Other
Method: AI
Process: Input

Background

- The use of machine learning/deep learning is advancing, and its application is progressing not only in industrial and commercial applications but also in R & D areas such as new material development.
- **Quantum computers, which have advantages in large scale and high speed computation, have been applied to machine learning.**
  - ✓ One direction is for quantum computers to speed up learning of "classical data" such as text and image data in machine learning and LLM learning in generative AI.
  - ✓ The other is **efficiency improvement through direct analysis and learning of quantum data and its superposition state by a quantum computer,** such as quantum states of physical systems (wave functions described by quantum mechanics, such as electronic states in molecules) and programs for quantum computers, as in this project.

Issues and motivation to be solved

- The strength of quantum computers in directly processing quantum states, such as simulating quantum mechanical processes in physical systems, motivates quantum machine learning on quantum data.
- **For this purpose, quantum machine learning is required by combining quantum sensors that input experimental data to a quantum computer with quantum computer processing.**
- In light of the above, Google used NISQ machines, which are affected by noise, to conduct **a study to compare the prediction performance of quantum data obtained from physical experiments that are stored in a quantum computer and trained by a quantum machine learning algorithm without performing any measurement that destroys the quantumness (superposition state), and the prediction performance of learning after converting the data to classical data measured by a quantum computer**

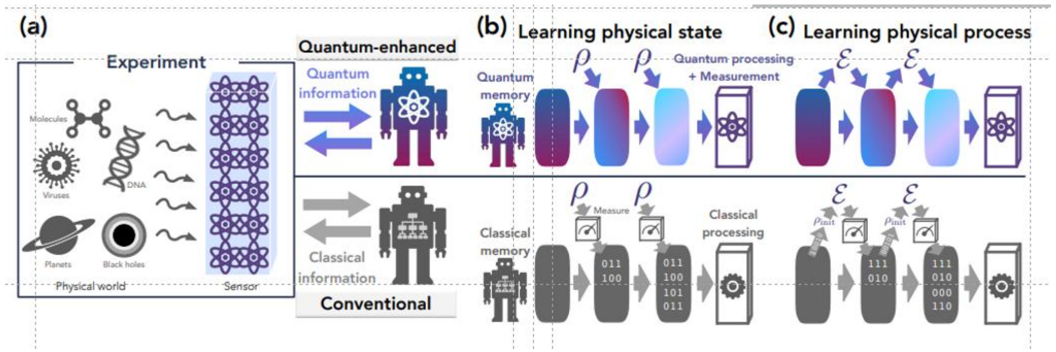
Reference: J-STAGE "Machine learning using quantum computers" (https://www.jstage.jst.go.jp/article/oubutsu/93/1/93_19/_pdf/-char/ja)

Google:
Using quantum data to predict the properties of physical systems with higher accuracy [2022/6] 2/3

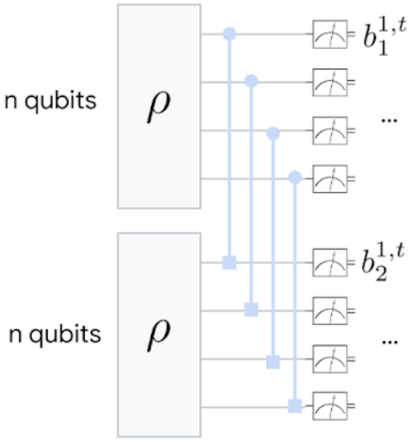
Industry	Other
Method	AI
Process	Input

Problem setting as a quantum computer

- Without measuring the wave function of the physical system in the superposition state, **learning by directly inputting 'quantum data' holding the quantum state to quantum machine learning** was performed.
  - ✓ In machine learning using classical computers, a physical system is learned using classical data whose quantum state is destroyed by measurement.
- **Using Quantum Sensors to Extract Experimental Data from Physical Systems for Quantum Machine Learning**
- The HW is powered by Google's Sycamore quantum processor.



Comparison of Quantum and Classical Machine Learning Algorithms



Basic schematic of a quantum machine learning algorithm
(stores two copies of a quantum state and uses Bell measurements to entangle each pair and measure their correlation)

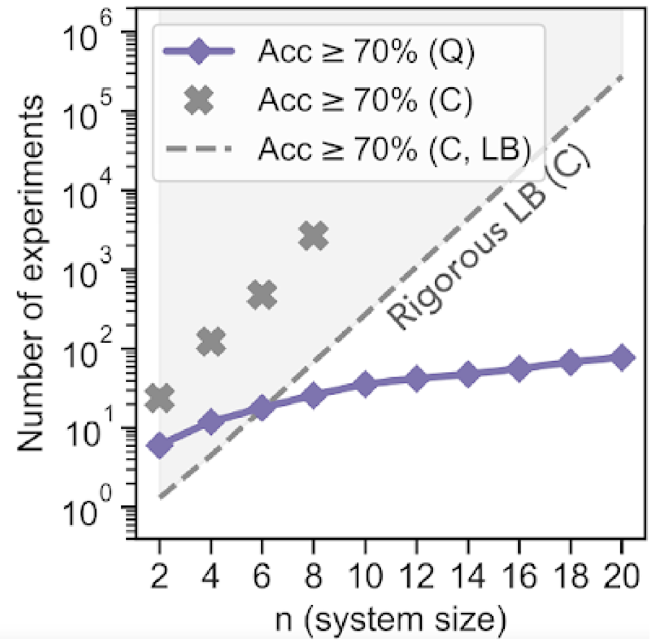
See: Science"Quantum advantage in learning from experiments" (https://www.science.org/doi/10.1126/science.abn7293),
J-STAGE "Machine Learning with Quantum Computers" (https://www.jstage.jst.go.jp/article/oubutsu/93/1/93_19/_pdf/-char/ja)

Google: Using quantum data to predict the properties of physical systems with higher accuracy [2022/6] 3/3

Industry: Other
Method: AI
Process: Input

Expected business benefits

- Regarding information (wave function) of physical systems that can be predicted by machine learning, **the difference between quantum and classical machine learning in the number of experiments (training) required to achieve 70% prediction accuracy grows exponentially with system size**
- **Combining quantum sensors and memory with quantum computers will accelerate efficiency with quantum machine learning**
- **Quantum machine learning may be used to predict the properties of physical systems with high accuracy, which is difficult in classical machine learning from the viewpoint of machine power and resources.**
  - ✓ However, quantum memory that can maintain coherence for a long time is still under development, and further research and breakthroughs such as connection to quantum computers are required.



Experimental Comparison of Quantum and Classical Machine Learning for predicting observables of quantum states.

- Q: Data from a quantum computer is directly stored in quantum memory without being “measured ” and learned using QML algorithms
- C: “Measured ” quantum computer data (classical data) is stored in classical memory and machine learning is executed
- C, LB: Theoretical lower limit of the number of experiments required for classical learning

Reference: Fujitsu Limited, "Up to this point, HPC✕ Electromagnetic Field Analysis" (https://www.hpci-office.jp/documents/workshop/cae-ws.240308_Kochibe.pdf)

Softbank: Communication Service Fault Diagnosis System Using Quantum Kernel Learning 【2024/8】1/3

Industry: Other
Method: AI
Process: model learning

Background

- In recent years, in addition to the advancement of corporate digital transformation (DX) and the penetration of remote work, the combination of ultra-high-speed, large-capacity transmission technology and edge computing technology in Beyond 5G/6G is expected to realize a data-driven society, and **the quality of the communication network is one of the important indicators** to support them.
- Due to the expansion of network demand and other factors, the equipment configurations of telecommunication carriers are becoming larger and more complex. **Automation using advanced computing technology is being studied, but classical computers have issues with efficiency and vulnerability to energy consumption and computational complexity, and quantum computers are expected to be more advanced and faster,** using AI called MLOps*.

MLIps *: Coined from the combination of machine learning (ML) and operations (Ops), this term refers to a pipeline in the development and operation process using machine learning.

Issues and motivation to be solved

- **Demonstration of a communication service fault diagnosis system using quantum machine learning** was conducted using a data set extracted from logs of a system operating on a commercial network.

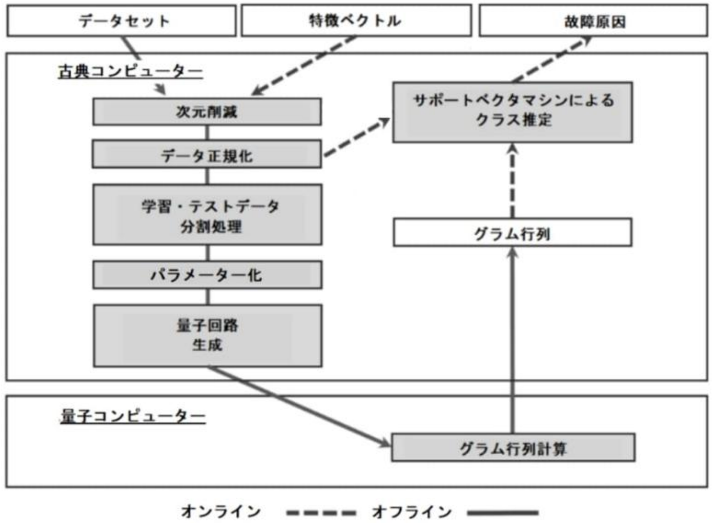
Reference: Softbank "Demonstration of communication service fault diagnosis system using quantum machine learning" (https://www.softbank.jp/corp/technology/research/story-event/062/)

Softbank: Communication Service Fault Diagnosis System Using Quantum Kernel Learning 【2024/8】2/3

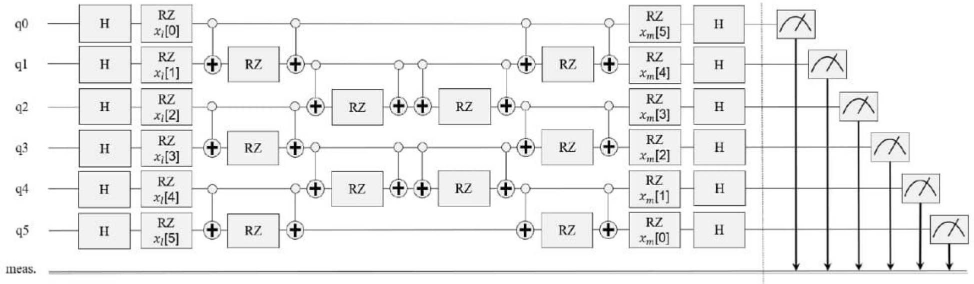
Industry	Other
Method	AI
Process	model learning

Problem setting as a quantum computer

- **The quantum computer is used to generate a Gram matrix by performing a round-robin inner product calculation on the number of failure patterns in the training data** while performing an operation to estimate the cause of failure for an unknown feature vector in an online process.
- **A unique quantum entanglement control circuit (patent pending) has been devised for kernel generation by quantum kernel learning, and the performance of quantum computers has been derived for more general-purpose data.**
- HW utilizes **IBM's superconducting gated quantum computer (IBM Quantum System One: IBM-Kawasaki 127 qubits) and Q-CTRL's error suppression system**



Scope of use of quantum computers in this initiative



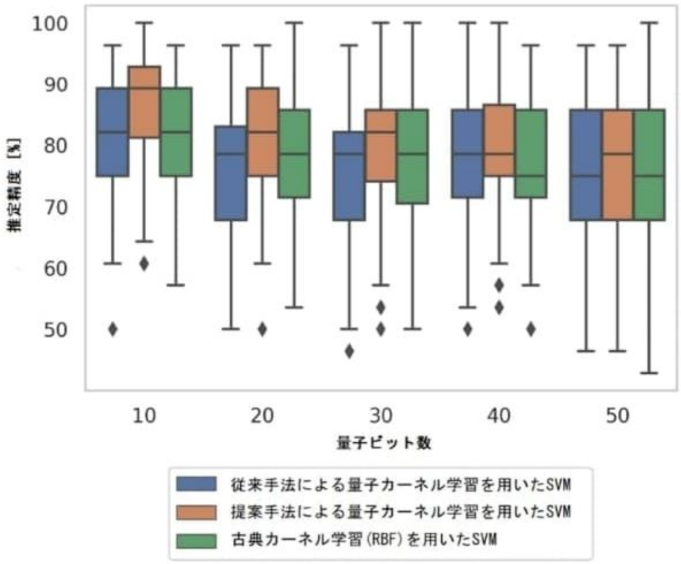
Proposed Quantum Kernel Learning Circuit

Reference: Softbank "Demonstration of communication service fault diagnosis system using quantum machine learning" (https://www.softbank.jp/corp/technology/research/story-event/062/)

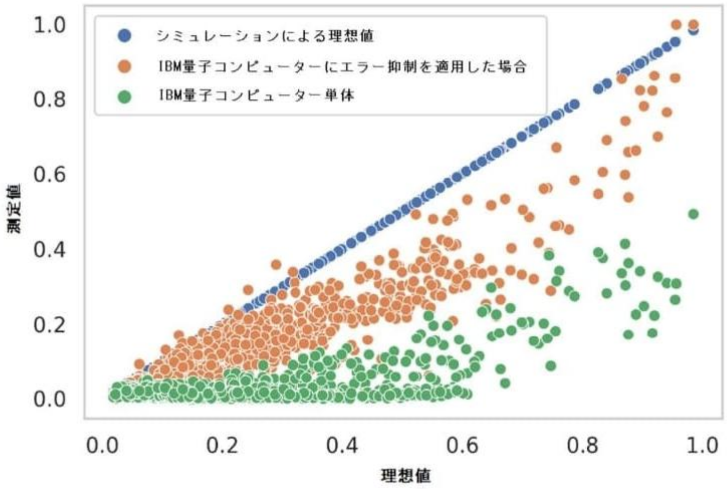
Softbank: Communication Service Fault Diagnosis System Using Quantum Kernel Learning 【2024/8】3/3

Expected business benefits

- The proposed method shows superior performance compared with SVM using conventional quantum kernel learning and SVM using classical kernel learning. Comparing the average values of the evaluation results for all qubit numbers, the conventional quantum kernel learning is 77%, the proposed quantum kernel learning is 81%, and the classical kernel learning is 78%, and the proposed method shows the best results.
- Improved quantum kernel learning algorithms and error suppression demonstrate the practical performance of quantum computers.



Comparison of failure cause estimation performance evaluation by a tensor network simulation



Effect of Error Suppression in Gram Matrices at 30 Qubits

Reference: Softbank "Demonstration of communication service fault diagnosis system using quantum machine learning" (https://www.softbank.jp/corp/technology/research/story-event/062/)

NTT DATA:
Improvement of Robot Arm Control Using Quantum Reinforcement Learning [2022/11] 1/3

Industry: Other
Method: AI
Process: model learning

Background

- Reinforcement learning has emerged as an interesting method for controlling the movements of robotic arms, but **it is not ready for global application in learning diverse control functions due to two factors: the search strategy and the slow learning speed.**
- **More software-based control solutions with low-cost sensors have been pursued to achieve autonomous robot motion.**
- The hope is that **using learning-based techniques to control robots** will allow **robots to move into less structured environments, process unknown objects, and be better suited for multiple tasks** so that **instead of human pickers, they can select items of various sizes and shapes**.

Issues and motivation to be solved

- **Deep reinforcement learning (DRL) is attracting attention as a promising method** that combines deep learning (DL) and reinforcement learning * (RL). Since deep reinforcement learning is computationally intensive, **the computational resources and generalization capability of quantum computers are expected for practical application in the real world.**
  - ✓ **Generalization capability refers to the ability to leverage previous knowledge from the source environment to achieve good performance in the target environment and its applicability to flexible, long-term autonomy, and is considered to be a necessary step in creating artificial intelligence that behaves like humans**

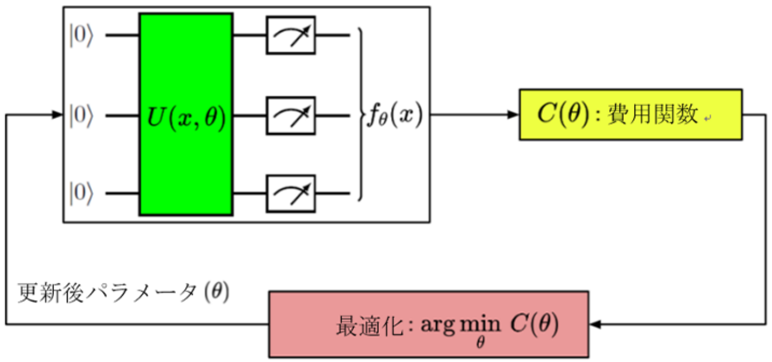
Reinforcement learning *: A method that enables a computer agent to perform tasks through a dynamic environment and repeated trial and error interactions

Reference: NTT Data "Enhancement of Reinforcement Learning by Quantum Computation for Robot Arm Control" (https://www.nttdata.com/jp/ja/trends/data-insight/2023/031601/)

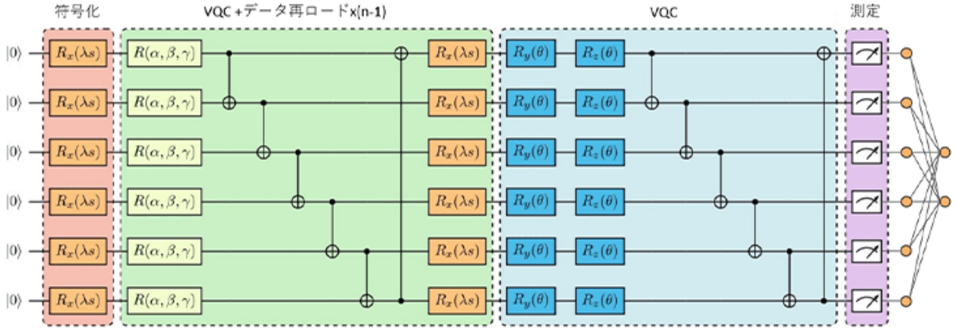
Improvement of Robot Arm Control Using Quantum Reinforcement Learning [2022/11] 2/3

Problem setting as a quantum computer

- **The use of quantum computers in improving robot arm control is variational quantum algorithms.**
  - ✓ A variational quantum algorithm is an algorithm that produces a quantum circuit that can perform a desired task by sequentially adjusting the configuration of the quantum circuit by a classical computer while monitoring the output of the quantum circuit as appropriate.
- In this research, **Variational quantum algorithm was applied to Soft Actor Critic (SAC), which is one of the state-of-the-art reinforcement learning methods for continuous control**.
- The verification is carried out using digital simulation of quantum circuits.



variational quantum algorithm



Actor Components Architecture
quantum-classical hybrid type of SAC

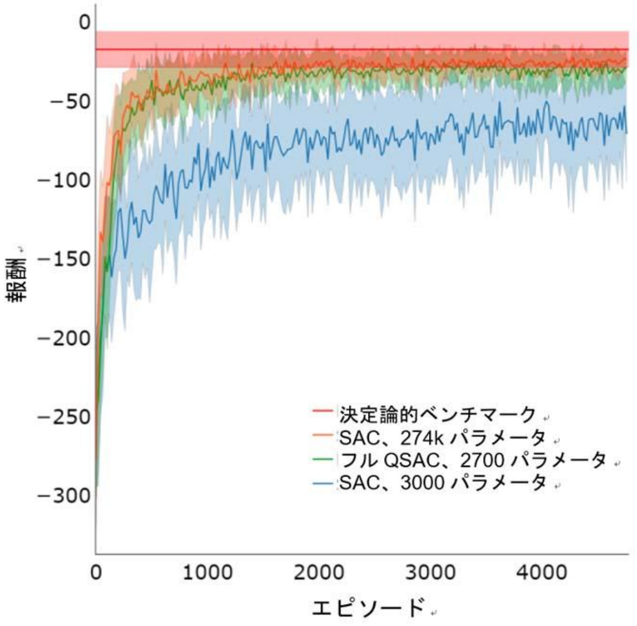
Reference: NTT Data, “Enhancement of Reinforcement Learning by Quantum Computation for Robot Arm Control ” (https://www.nttdata.com/jp/ja/trends/data-insight/2023/031601/), IEICE,“ Variational Quantum Algorithms and Quantum Machine Learning ” (https://app.journal.ieice.org/trial/104_11/k104_11_1166/index.html)

NTT DATA:
Improvement of Robot Arm Control Using Quantum Reinforcement Learning [2022/11] 3/3

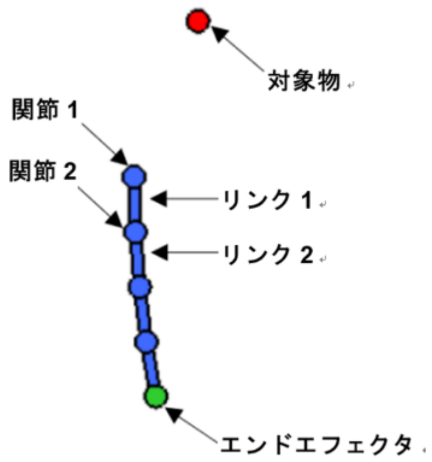
Industry	Other
Method	AI
Process	model learning

Expected business benefits

- Through numerical simulations, **we show that actor-critic quantum strategies perform better than classical models of similar architectures, and there is a clear quantum advantage in the number of parameters that can be learned** on benchmark robot control tasks.
- However, the above is only verification in a test environment.



Learning curves of classical and quantum-classical SAC architectures tested in a robotic arm environment



Virtual two-dimensional four-joint robot arm tested in the study

Reference: NTT Data "Enhancement of Reinforcement Learning by Quantum Computation for Robot Arm Control" (https://www.nttdata.com/jp/ja/trends/data-insight/2023/031601/)

BlueMeme: Lowering the Cost of LLM in Biomedical Information Analysis 【2023/6】1/2

Industry: Other
Method: AI
Process: inference

Background

- **In recent years, biomedical information analysis *, which analyzes biological data such as genome data and clinical information such as medical records of patients by computational science techniques such as machine learning and statistics, has attracted attention.**
  - ✓ Biomedical information analysis refers to the use of information technology to analyze and process biological data in the fields of biology, medicine, and life sciences.
- Moreover, **LLMs (large-scale language models), which are being developed and popularized, have begun to be used in biomedical information analysis**, but the economic burden of large computational resources and high costs has made it virtually **difficult for SMEs, local governments, and research institutes to develop and operate LLMs.**

Issues and motivation to be solved

- **Dramatically reduce LLM operating costs with quantum AI**
  - ✓ learn and infer LLMs on quantum computers that were learned on classical computers
- By significantly reducing the number of LLM parameters, **significantly reduce the cost of running the model**
- **More research institutions and companies can contribute to clinical applications** by developing and operating biomedical language models inexpensively.

Expected business benefits

- **The inference cost exceeds the learning cost when deploying the trained model through APIs, and** ChatGPT is estimated to cost more than $700,000 (approximately ¥100 million) per day to operate, and supporting customer service using GPT -4 **is estimated to cost SMEs more than $21000 (approximately ¥3 million) per month**
- The latest research in the field of quantum AI **demonstrates the quantum advantage of implementing LLMs on a quantum computer to train and reason with less memory than would be required on a classical computer**.
- By developing and operating biomedical language models cheaply, **we aim to enable more research institutions and companies to contribute LLM to clinical applications.**

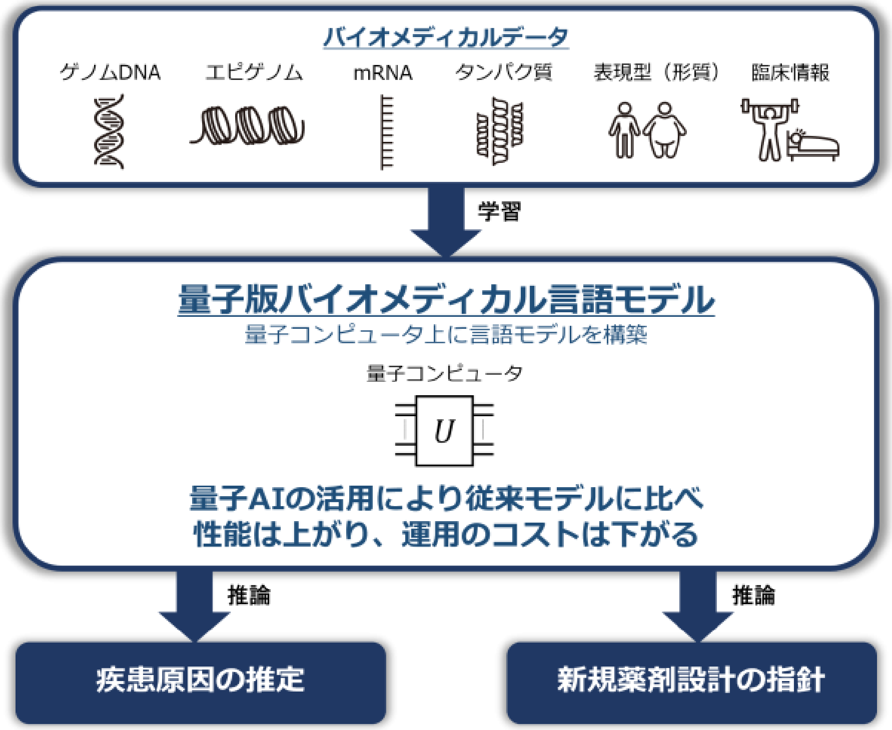
Reference: DS100"BlueMeme and Kyushu University collaborate on quantum AI language models" (https://ds100.jp/news/2023/06/21/bluememe%E3%81%A8%E4%B9%9D%E5%B7%9E%E5%A4%A7%E5%AD%A6%E3%80%81%E9%87%8F%E5%AD%90ai%E3%82%92%E7%94%A8%E3%81%84%E3%81%9F%E5%A4%A7%E8%A6%8F%E6%A8%A1%E8%A8%80%E8%AA%9E%E3%83%A2%E3%83%87%E3%83%AB%E6%A7%8B/), bluemememe "Initiatives in the field of biomedical information analysis using quantum computing " (https://www.bluememe.jp/research-and-development/)

BlueMeme: Lowering the Cost of LLM in Biomedical Information Analysis 【2023/6】2/2

Industry	Other
Method	AI
Process	inference

Problem setting as a quantum computer

- **The latest omics data with high precision and high resolution is used as a learning basis of omics language model using quantum AI technology.**
  - ✓ Omics language models are artificial intelligence models that train and develop vast amounts of omics data (information about a comprehensive set of biomolecules) to specialize in biological data analysis.
- Quantum AI reduces the number of parameters in LLMs to **reduce the computing costs of learning and inference**
- We will conduct performance verification using computational infrastructure such as simulations on GPU supercomputers and real quantum computers.



Omics language model using quantum AI technology

Reference: bluemememe "Initiatives in the field of biomedical information analysis using quantum computing" (https://www.bluememe.jp/research-and-development/)

Quemix: Image Generation Using Quantum Neural Networks [2023/11] 1/3

Industry: Other
Method: AI
Process: inference

Background

- Generative AI that learns and provides the best/new answers The need for AI is expanding, and image generation that generates high-dimensional data is also realized.
- **Due to the need for large-scale operations such as image generation using generative AI, demand for computing resources and energy will increase, and there is concern about an increase in CO2 emissions.**
  - ✓ **Of the CO2 emitted by AI models, the majority** is [* 1,] which is generated when **users use AI,** not when training AI models.
  - ✓ Image AI requires far more energy than text generation, and **using diffusion models to generate 1000 images would emit as much CO2 as driving an average gas-powered car for about 6.6 kilometers,** says Stable Diffusion.

Issues and motivation to be solved

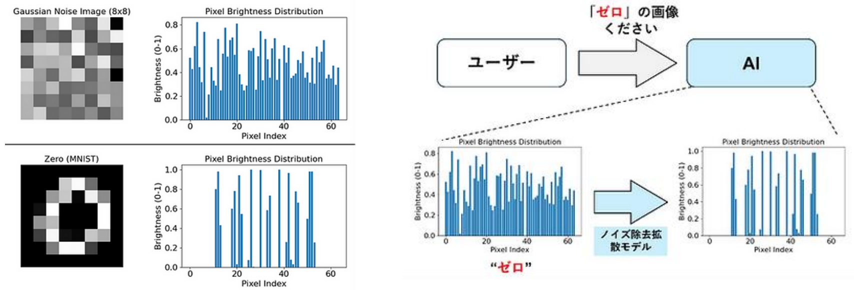
- The diffusion model using the classical neural network model is widely used in image and video generation.
  - ✓ **In the diffusion model, noise is removed from original image data (pixel value) including random noise and converted into a desired image.**
- **However, quadratic scaling of the image data** (e.g., an 8 pixel image requires 64 elements) makes **high resolution images such as 4K images require simultaneous processing of large amounts of data, which is difficult for classical computers** and even worse for video generation
- Thus, the quantum algorithm vendor, **Quemix, replacing classical neural networks with quantum neural networks, aims at the possibility of large-scale image and video generation taking advantage of the advantages of simultaneous parallel computing of quantum computers.**

*1: MIT Technology Review"AI image generation consumes as much energy as a fully charged phone" (https://www.technologyreview.jp/s/323271/making-an-image-with-generative-ai-uses-as-much-energy-as-charging-your-phone/)
Quemix "Diffusion model based on quantum neural network with channel attention" (https://www.quemix.com/notes011)

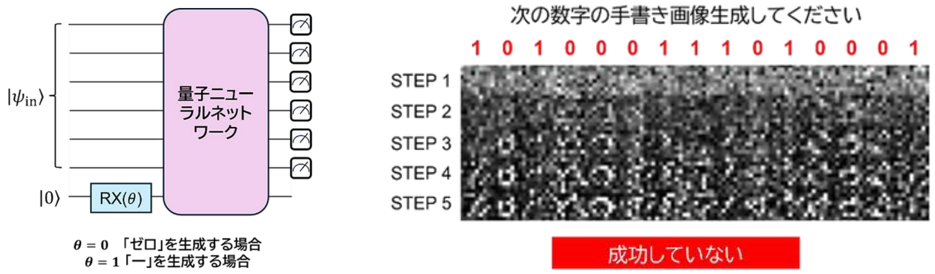
Quemix: Image Generation Using Quantum Neural Networks [2023/11] 2/3

Problem setting as a quantum computer

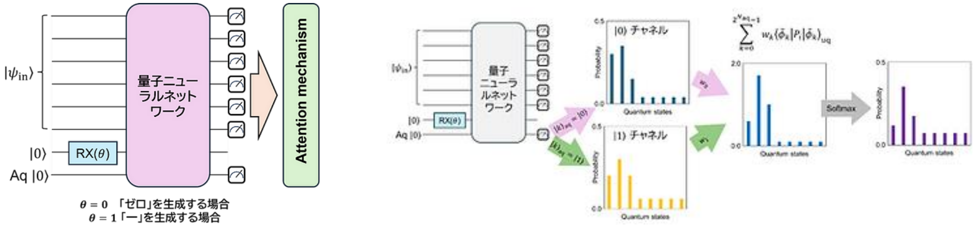
- Diffusion Model Using Classical Neural Network
  - ✓ Images are represented as two-dimensional matrices, with matrix elements corresponding to pixels.
  - ✓ When the AI is asked for a handwritten “zero, ” it generates an image by **converting the pixel values of a matrix representation random noise image into a handwritten“ zero.**
- Diffusion model using quantum neural network
  - ✓ **The 8 million elements needed to generate a 4 K image** would be difficult to process simultaneously with a classical neural network, **but a quantum computer could be used to process them at 23 bit speeds.**
  - ✓ Image generation, on the other hand, requires denoising
- **Diffusion Model Using Quantum Neural Network with Denoising Performance**
  - ✓ Denoising is a non-unitary operation that cannot be handled by the unitary operations allowed by quantum computers
  - ✓ Thus, large-scale operations are performed on quantum computers, and **we introduce a channel attention function that performs nonunitary operations to remove noise on classical computers.**



Generating Handwritten “0 ” by Diffusion Model in Classical NN Can Generate Denoised Output



Quantum circuit generating handwritten "0" or "1" via quantum neural network diffusion model and corresponding output (image generation fails due to noise)



Introducing denoising function (channel attention) to diffusion model of quantum NN

Quemix "Diffusion model based on quantum neural network with channel attention" (https://www.quemix.com/notes011)

Quemix: Image Generation Using Quantum Neural Networks [2023/11] 3/3

Expected business benefits

- **QCNN performed better, outperforming the traditional approach of using a feedforward neural network as an additional post-processing**
- **Image generation by a classical computer is difficult with high-resolution images of 4K resolution or higher.** At 4 K resolution and above, vectors of about 8 million elements in length must be processed simultaneously during the denoising and spreading process. This challenge is **exacerbated by the 60~120 images per second video required for modern video production**.
  - ✓ A quantum computer could process the 8 million elements needed to produce a 4 K image in as little as 23 qubits.

Quemix "Diffusion model based on quantum neural network with channel attention" (https://www.quemix.com/notes011)

Hakuhodo: AI Model Compression for 3D Model Conversion of Images Using NeRF Model 【2024/5】1/2

Industry	Other
Method	AI
Process	inference

Background

- **NeRF (Neural Radiance Field)** (*1) **refers to a 3D reconstruction technique that can generate a free-viewpoint image from a subject image. The NeRF model can represent a free-viewpoint image as a continuous function that maps three-dimensional coordinates and viewpoint direction to color and density using a neural network trained on images.**
- The Marketing Technology Center (MTC), the R & D division of Hakuhodo DY Holdings, is cooperating with blueqat to **explore the potential use of quantum computers in advertising and marketing in anticipation of the arrival of the quantum computer era in the future.**

Issues and motivation to be solved

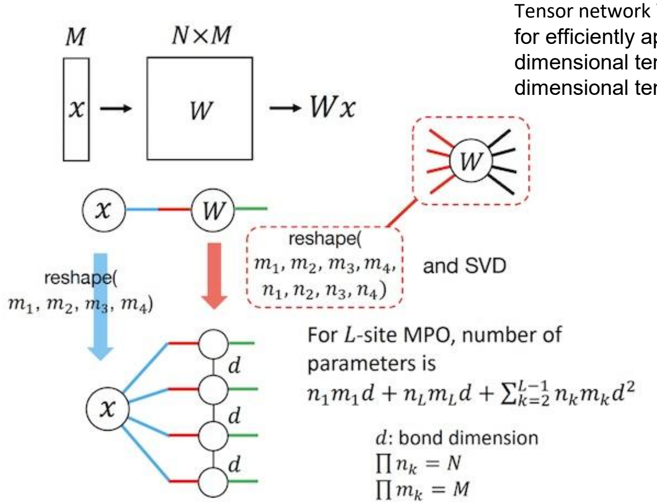
- **In the field of machine learning, reliance on high-performance GPUs and their associated energy consumption is a key sustainability issue. Furthermore, for applications that require strict response times and security standards, the ability to perform tasks locally without cloud resources is critical. Various model compression techniques have been introduced to address these challenges.**

NeRF* 1: A 3D representation method that maps 3D coordinates and viewing direction to color and density

Problem setting as a quantum computer

- **Tensor network**, *2 and **ability to extract features effectively from high dimensional space** are attracting attention in the field of machine learning.
  - ✓ By applying tensor decomposition techniques to the large number of weighted parameters in a neural network, **features can be extracted efficiently and the number of parameters can be reduced.**
- We aim to **compress NeRF (Neural Radiance Field) using MPO decomposition** because there is a precedent of successfully reducing model size when applying Tensor-Train (MPO) decomposition (below) to LLM (Large Language Model).

Tensor network *2: Refers to a method for efficiently approximating a high-dimensional tensor by using a low-dimensional tensor



MLP layer replaced by Tensor-Train (MPO) layer

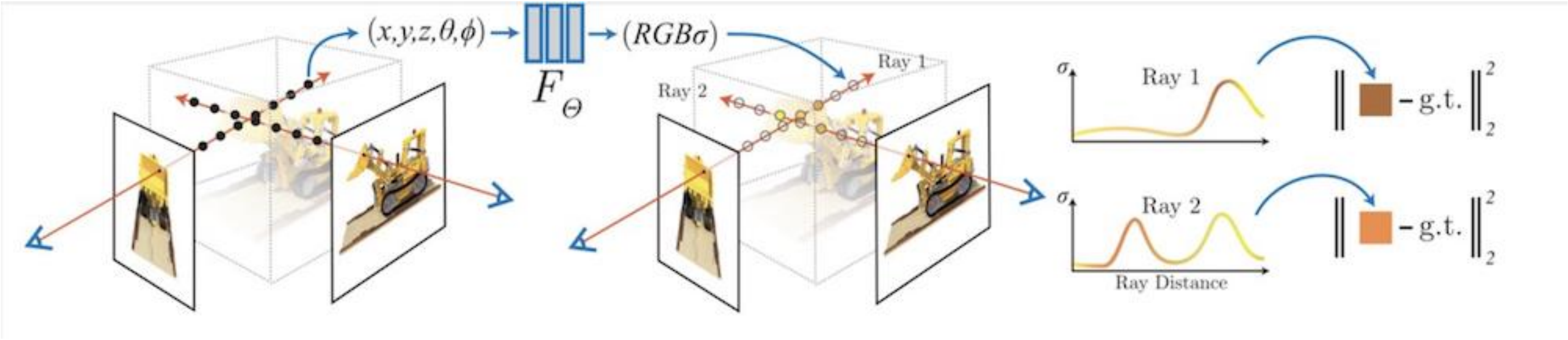
Reference: Hakuhodo "Hakuhodo DY Holdings demonstrates compression of NeRF models using a tensor network that can be applied to quantum gate computers, enabling efficient 3D image generation" (https://www.hakuhodody-holdings.co.jp/news/corporate/2024/05/4809.html), blueqat"Hakuhodo DY Holdings/blueqat demonstrates compression of NeRF models using tensor network technology. Presented at the SQAI-NCTS International Workshop" (https://blueqat.com/blueqat_official_news_ja/0233c282-1f78-447a-ac5f-bc4727e33857)

Hakuhodo: AI Model Compression for 3D Model Conversion of Images Using NeRF Model 【2024/5】2/2

Industry	Other
Method	AI
Process	inference

Expected business benefits

- Applying tensor networks to NeRF models **demonstrates efficient reduction in model size while maintaining rendering quality**
- This work shows the applicability of tensor network for the efficiency improvement of image rendering. Tensor networks are also known to work well with quantum circuits, **leading us to envision that when quantum gate computers are completed in the future, this technology can be applied directly.**



Schematic diagram of NeRF image generation and rendering method

Reference: Hakuhodo "Hakuhodo DY Holdings demonstrates compression of NeRF models using a tensor network that can be applied to quantum gate computers, enabling efficient 3D image generation" (https://www.hakuhodody-holdings.co.jp/news/corporate/2024/05/4809.html), blueqat"Hakuhodo DY Holdings/blueqat demonstrates compression of NeRF models using tensor network technology. Presented at the SQAI-NCTS International Workshop" (https://blueqat.com/blueqat_official_news_ja/0233c282-1f78-447a-ac5f-bc4727e33857)

Keio University, TOPPAN Holdings:Demonstration of effectiveness of quantum machine learning for quality inspection of agricultural products [2025/3] 1/2

Industry	Other
Process	Other
Method	AI

Background

- In the field of image inspection in manufacturing and inspection processes, there is a need for a technology for discriminating between normal and abnormal products with high accuracy. Agricultural products in particular have large variations in shape and internal structure, making it difficult to collect and label sufficient training data.
- In quantum machine learning, the "quantum kernel method" is drawing attention as an approach that can improve separation capability even for small data by mapping data to a high-dimensional quantum feature space.
- Keio University and TOPPAN Holdings verified the effectiveness of SVM using quantum kernel for internal vine cracking of apple

Issues and motivation to be solved

- In agricultural and product quality inspection, it is necessary to detect various abnormal patterns by learning from small amounts of data, which is a difficult problem with conventional machine learning.
- Utilizing the classification capability of quantum kernels in a high-dimensional space, we will explore the applicability of quantum kernels to non-destructive testing of agricultural products.

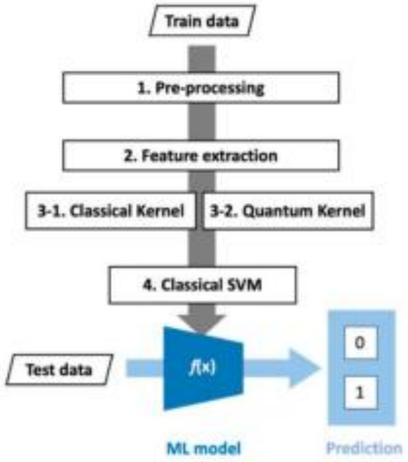


Image of the inspection process using classical and quantum kernel methods

Reference: Keio University: "Realization of High-precision Abnormality Detection Technology Using Quantum Kernel ― Demonstration of the Effectiveness of Quantum Machine Learning with Small Data and Promotion of Manufacturing DX ―" (https://www.keio.ac.jp/ja/press-releases/files/2025/3/24/250324-1.pdf)

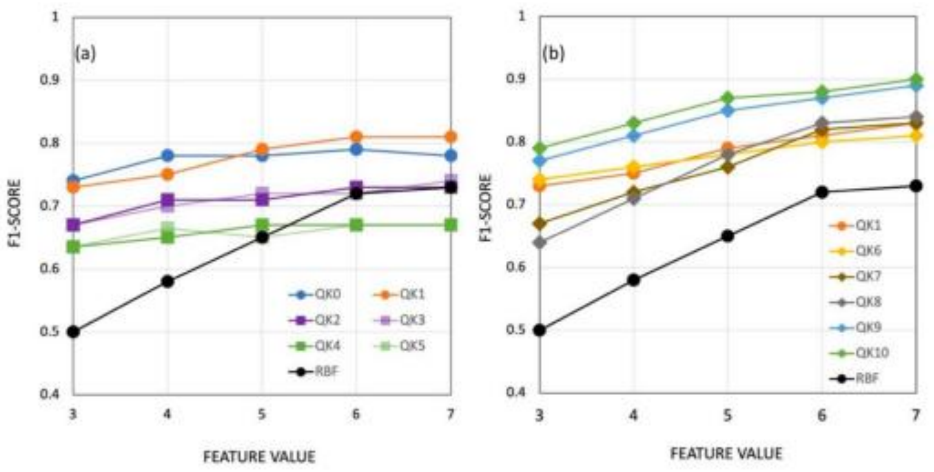
Keio University, TOPPAN Holdings:Demonstration of effectiveness of quantum machine learning for quality inspection of agricultural products [2025/3] 2/2

Problem setting as a quantum computer

- Using a dataset of light transmissive images to detect internal cracks in apples that cannot be seen visually
- Preprocessing and feature extraction are performed on the data, and machine learning is performed using a Support Vector Machine (SVM) embedded with a quantum kernel.

Expected business benefits

- Application not only to agricultural products but also to quality inspection in the manufacturing industry, technology deployment to fields requiring abnormality detection with small amounts of data, and promotion of manufacturing DX (digital transformation)



Relationship between feature number and F1 score based on quantum simulator calculation result
It is shown that the quantum kernel (QK9, QK10) outperforms the classical kernel (RBF).

Reference: Keio University: "Realization of High-precision Abnormality Detection Technology Using Quantum Kernel ― Demonstration of the Effectiveness of Quantum Machine Learning with Small Data and Promotion of Manufacturing DX ―" (https://www.keio.ac.jp/ja/press-releases/files/2025/3/24/250324-1.pdf)

Qunasys: Prevention of Resonance by Natural Frequency Analysis Using Quantum Phase Estimation 【2023/07】1/2

Industry: Other

Method: Simulation

App Classification: CAE (Stress Analysis)

Background

- QunaSys is **Examining the Applications of Quantum Computers in the CAE Field** and discusses the potential applications of quantum computers, their impact, and comparisons with classical computation, mainly from a technical perspective, in two phases of the quantum computer paradigm: the NISQ era and the FTQC era. A CAE study group was held in which JX Oil Exploration Co., Ltd. and Murata Manufacturing Co., Ltd. participated to **gather suggestions on the direction of utilization based on the characteristics of quantum computers.**
- **The quantum phase estimation algorithm * has become a source of exponential quantum acceleration in many applications including quantum chemistry.**
- Natural frequency analysis of structures is **of industrial importance to prevent damage and noise from resonance.**
  - ✓ Natural frequency analysis is an analysis that generates resonance when the frequency of the input load coincides with the natural frequency of the structure side, preventing unpleasant vibration, noise, and damage.

Quantum phase estimation algorithm *: A method for estimating the eigenvalue associated with a given eigenvector of a unitary operation

Issues and motivation to be solved

- Since quantum phase estimation can solve eigenvalue problems, it has applications in quantum chemistry, or **if we can find other eigenvalue problems that quantum computers can solve exponentially faster, it will open up a promising use case.**
- In this project, **application to natural frequency analysis** is being considered as a new target.

Reference: Qunasys "Natural frequency analysis by quantum computer using quantum phase estimation algorithm" (https://unit.aist.go.jp/g-quat/ja/events/img/CAE_20240509-10/20240510_10_Kanno.pdf)

Qunasys: Prevention of Resonance by Natural Frequency Analysis Using Quantum Phase Estimation 【2023/07】2/2

Industry Other

Method Simulation

App Classification CAE (Stress Analysis)

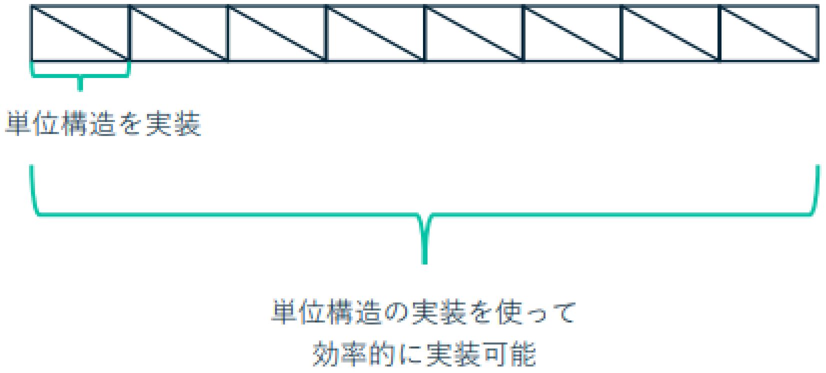
Problem setting as a quantum computer

- The purpose of this project is to **propose natural frequency analysis** as a new application of the quantum phase estimation algorithm.
- Calculated LV1 (constant spring constant) and LV2 (two types of spring constant) for N spring-connected mass points connected in one dimension
  - ✓ After preparing the input by performing coarse calculation on a classical computer, we implemented quantum phase estimation at the gate level for a one-dimensional system.
  - ✓ An efficient implementation for repetitive systems is also proposed.
- The HW used is not specified, but since QunaSys is working on a gate-based quantum computer, it is assumed to be a gate-based quantum computer.

Expected business benefits

- Calculations were performed for LV1 (constant spring constant) and LV2 (two types of spring constant) for N spring-connected mass points connected in one dimension.
- For a one-dimensional system, we implemented quantum phase estimation at the gate level and **showed exponential acceleration throughout the calculation.**
  - ✓ Qubitization * was utilized for the natural frequency analysis, and the gate number was O (log N) for N mass points (O (N) for a classical computer) in the whole quantum circuit.

Qubitization *: A method to convert Hamiltonian into a form that can estimate quantum phase using fewer resources than previous methods



Systems where this approach can be applied repeatedly

2^n	code distance	# of physical qubits	runtime
2^{32}	25	$\sim 5.2 \times 10^5$	~ 23 min.
2^{64}	25	$\sim 8.5 \times 10^5$	~ 45 min.
2^{128}	27	$\sim 17.5 \times 10^5$	~ 90 min.

n number and estimated computation time in LV2

due to strong wind resonance
Collapsed Tacoma Bridge (1940)

Natural frequency analysis by quantum computer using quantum phase estimation algorithm (https://unit.aist.go.jp/g-quat/ja/events/img/CAE_20240509-10/20240510_10_Kanno.pdf), qmedia"What are the strengths of "lab-initiated ventures"? Two companies working on quantum computers and quantum annealing look ahead to social implementation" (https://www.qmedia.jp/qunasys-jij-interview/)

KandaQuantum: Fast Generation of Large Gantt Charts Using a Unique Quantum LLM 【2023/7】1/2

Industry	Other
Method	AI, combinatorial optimization
Process	inference

Background

- In recent years, LLM (Large Scale Language Model) has been rapidly developed and utilized in a wide range of applications, but **it is difficult to answer optimization problems with complicated logic with high precision, and the application range is limited**.
- **The schedule optimization by conventional LLM was not effective for large projects for the following two reasons.**
  - ① Dealing with multiple people and tasks requires a lot of computation
  - ② Accuracy drops significantly as schedule complexity increases

Issues and motivation to be solved

- We aim to solve the following problems by utilizing quantum technology.
  - ✓ The learning information is fed into mathematical models and LLM prompts, **generating itself with quantum LLMs to reduce computational complexity**
  - ✓ Combining LLM and Quantum Technologies to **Enable Efficient Use of Learning Data**
  - ✓ Effective solution of the problem of computational complexity such as combinational explosion and **realization of multi-modal utilization of voice, image and text**
  - ✓ **Enable interactive communication with AI** by solving speed at large scale computations
  - ✓ Quantum technology **improves the accuracy of responses to logically-complex optimization problems and broadens applications.**

Problem setting as a quantum computer

- Quantum LLM (quantum annealing and quantum inspired technology) is strong in order receiving AI, no-code workflow AI and promanage AI.
- **In this project, large - scale, high - speed and high - precision Gantt chart generation was realized by quantum promotion AI “CalqPM" which combines LLM and pseudo - quantum technology.**
- Quasi-quantum technology is used to **simulate the characteristics of quantum computers based on mathematical models of mathematical optimization**
- This project uses pseudo quantum technology on a classical computer, but **even if it is replaced with a quantum computer such as D-wave, it can be operated without major changes to the mathematical model.**

```
プロジェクト内容
- 期間
    - 4ヶ月
- プロジェクトの目的
    - 保険業界のデジタル化を推進する
- プロジェクトの成果物
    - 4ヶ月後までに保険支援AIの企画、研究開発（PoC）、プレスリリースをする必要があります。
- 詳細
    - やることは企画コンサル、実証実験、通常開発、プレスリリースなど多岐にわたります。
    - プレスはPoC前に行います。実証実験開始前に行うことで、プロジェクトの認知度を高めることができます。
```

Input image to Quantum Professional Manager AI (employee information is also entered separately)

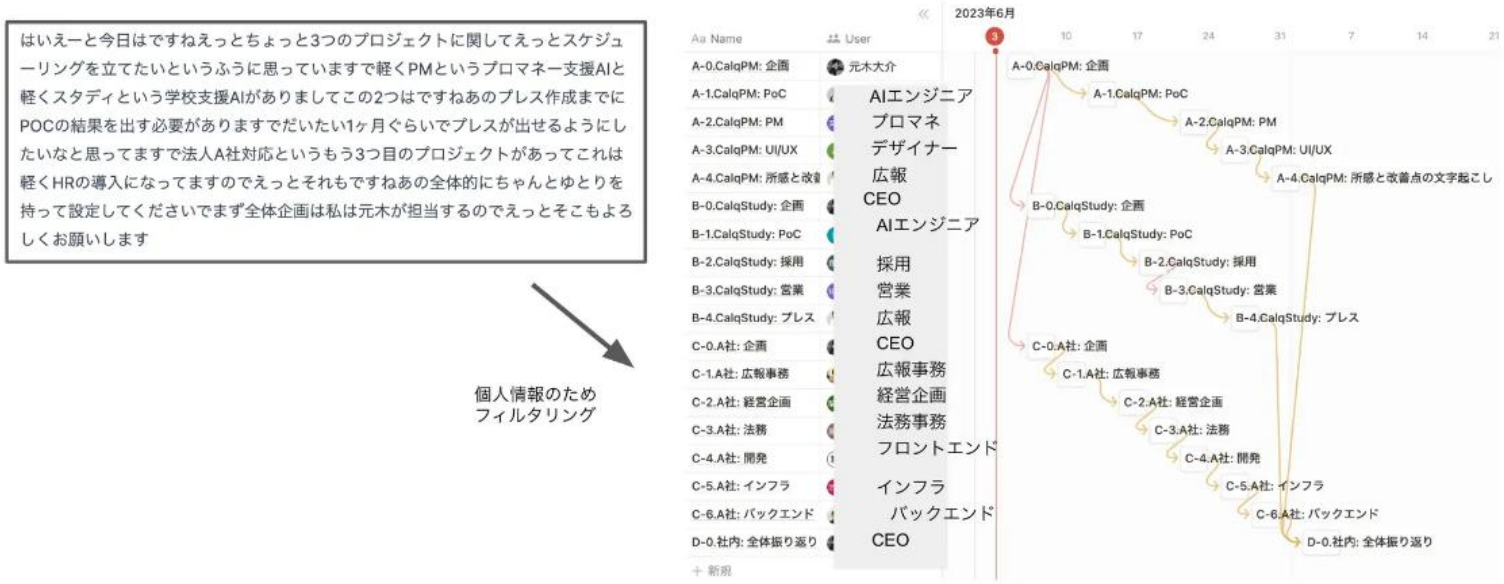
Reference: DIGITSL SHIFT TIMES"KandaQuantum uses AI to automatically generate Gantt charts" (https://digital-shift.jp/flash_news/FN230626_3), PRTIMES"Commenced the CalQamel Project, a domestic "quantum generation AI"" (https://prtimes.jp/main/html/rd/p/000000130.000082094.html)

KandaQuantum: Fast Generation of Large Gantt Charts Using a Unique Quantum LLM 【2023/7】2/2

Industry	Other
Method	AI, combinatorial optimization
Process	inference

Expected business benefits

- Gantt chart of 50 tasks in 4 months for 17 people **Gantt chart output in 4 minutes considering task dependency, job type matching and resource status**
- This QPR AI is expected to **contribute to improving the stability and speed of project promotion in large-scale networked projects,** such as agile projects, autonomous distributed organizations (DAO), and teal organizations.



Illustrative Output of Quantum Project manager AI corresponding to the speech input

Reference: PRTIMES"GPT-4 x Quantum: Promane AI, Notion in production" (https://prtimes.jp/main/html/rd/p/000000122.000082094.html)

Fujitsu: Evaluation of RSA Cryptanalysis【2023/01】1/2

Industry	Other
Method	cryptanalysis
Process	–

Background

- Based on **the security of public key cryptography (RSA cryptography, etc.) is the difficulty of the prime factorization problem**, 2,048 bit composite numbers are widely used.
  - ✓ *1 because the number of combinations that can be deciphered by classical computers is 829 bits.
  - ✓ The composite number of prime factorizations N=p x q(p and q are different prime numbers)
- **Although studies have been carried out to efficiently solve the prime factorization by classical computers, the number-field sieve method, which is the most asymptotically fast algorithm at present, requires quasi-exponential time for the digit length of the composite number N and is difficult to decipher.**
  - ✓ Even if a supercomputer is used by applying the number field sieve method to the prime factorization of 2,048 bit composite numbers, *2 is estimated to be required for several decades or more even for the fastest supercomputer (Linpack performance of 1018FLOPS).
- But **with the advent of quantum computers and the fast computable Shor algorithm, the RSA cipher has been shown to be breakable in a realistic amount of time,** and is now theoretically cracked.
  - ✓ **The complexity of the Shor algorithm is a polynomial of N digits in length** time, **exponentially accelerated from the computation time of a classical computer**

Issues and motivation to be solved

- **The advent of quantum computers threatens the security of cryptography, but there are few experimental cases to verify how much computational resources of quantum computers are actually required to decrypt RSA cryptography, making it difficult to estimate.**
- Thus, **Fujitsu has utilized a quantum simulator to demonstrate prime factorization to assess the security of a 2,048 bit RSA cipher.**

*1:「[Cado-nfs-discuss] Factorization of RSA-250」(https://web.archive.org/web/20200228234716/https:/lists.gforge.inria.fr/pipermail/cado-nfs-discuss/2020-February/001166.html)
*IEICE "Security in the Age of Quantum Computers: Trends in Quantum-Resistant Computer Cryptography " (https://app.journal.ieice.org/trial/106_11/k106_11_966/index.html)
Fujitsu Limited, "Successful Security Assessment of RSA Cryptography with Quantum Simulator" (https://pr.fujitsu.com/jp/news/2023/01/23.html)

Fujitsu: Evaluation of RSA Cryptanalysis【2023/01】2/2

Industry	Other
Method	cryptanalysis
Process	–

Problem setting as a quantum computer

- **Resource evaluation of quantum computer required to decode 2048 bit RSA cipher** generally used at present was carried out.
- In the computer experiments, **a general-purpose program for generating a quantum circuit that factorizes input composite numbers was implemented in a quantum simulator using Shor's algorithm**, and **a quantum circuit that factorizes several composite numbers from 10 bits to 25 bits was actually generated.**
- **Estimation of the computational resources of the quantum circuit required for factoring 2,048 bit composite numbers was performed from the computational resources required at that time.**
- Using our in-house developed **39 qubit quantum simulator** to perform prime factorization
  - ✓ The quantum simulator takes advantage of the high speed of the Fugaku supercomputer's A64FX CPU and Fujitsu's massively parallel computing technology

Expected business benefits

- **They** successfully factorized 96 prime numbers from N=15 to N=511, confirming that a general-purpose program can generate the correct quantum circuit.
- From the calculation resources required for a quantum circuit that factorizes several composite numbers from 10 bits to 25 bits, it was shown that **104 days of computation is required even if a quantum circuit with the following specifications is used** to factorize a 2,048 bit composite number.
  - ✓ Number of qubits: Approximately 10,000 qubits
  - ✓ Number of gates: approximately 2.23 trillion
  - ✓ Quantum computation steps: about 1.8 trillion
- However, because it is **difficult to develop a stable FTQC in the short term** at large scales and for long periods of time (104 days of keeping qubits intact), **the 2,048 bit RSA cipher is safe against the Shor algorithm**.

Fujitsu Limited, "Successful Security Assessment of RSA Cryptography with Quantum Simulator" (https://pr.fujitsu.com/jp/news/2023/01/23.html)

Appendix (1) List of quantum computer vendors

Major players in quantum technology 1/2

* The company names on this page are in English to ensure readability and consistency. For the official names and descriptions of each company, please refer to their official websites.

No.	Player Name	Country
1	1QBit	Canada
2	A*QUANTUM	Japan
3	ALIBABA DAMO HANGZHOU TECHNOLOGY	China
4	ALIBABA HOLDING	China
5	Alice & Bob	France
6	Alpine Quantum Technology	Austria
7	AMAZON TECHNOLOGIES	America
8	Anyon Systems	Canada
9	aQuantum Software Engineerig	Spain
10	Atom Computing	America
11	BEIJING BAIDU NETCOM SCIENCE & TECHNOLOGY	China
12	Beit	Poland
13	Bleximo	America
14	blueqat	Japan
15	BosonQ Psi	America
16	C12 Quantum Electronics	France
17	CLASSIQ TECHNOLOGIES	Israel
18	COLDQUANTA	America
19	D-WAVE SYSTEMS	Canada
20	eleQtron	Germany
21	Entropica Labs	Singapore
22	Fixstars	Japan
23	FUJITSU	Japan
24	GOOGLE	America
25	Groovenauts	Japan

No.	Player Name	Country
26	Haiqu	America
27	Hefei Origin Quantum Computing Technology	China
28	HITACHI	Japan
29	Horizon Quantum Computing	Singapore
30	HUAWEI	China
31	IBM	America
32	Infleqtion	America
33	INTEL	America
34	IonQ	America
35	IQM Quantum Computers	Finland
36	Jij	Japan
37	MICROSOFT TECHNOLOGY LICENSING	America
38	Multiverse computing	Spain
39	Nanofiber Quantum Technologies	Japan
41	NEC	Japan
42	Nord Quantique	Canada
43	NTT	Japan
44	NTT RESEARCH	Japan
45	OptQC	Japan
46	ORCA Computing	United Kingdom
47	ORIGIN QUANTUM COMPUTING TECHNOLOGY HEFEI	China
48	Oxford Ionics	United Kingdom
49	Oxford Quantum Circuits	United Kingdom
50	PASQAL	France
51	Photonic	Canada

Reference: Various public information

Major players in quantum technology 2/2

* The company names on this page are in English to ensure readability and consistency. For the official names and descriptions of each company, please refer to their official websites.

No.	Player Name	Country
52	PSIQUANTUM	America
53	Qblox	Netherlands
54	qBraid	America
55	QC design	Germany
56	QC Ware	America
57	Q-CTRL	Australia
58	QILIMANJARO QUANTUM TECHNOLOGY	Spain
59	Qrithm	America
60	Quandela	France
61	Quanmatic	Japan
62	Quantinuum	America
63	Quantum Benchmark	Canada
64	Quantum Brilliance	Australia
65	Quantum Circuits	America
66	Quantum Computing	America
67	QUANTUM MACHINES	Israel
68	QUANTUM MOTION TECHNOLOGIES	United Kingdom
69	Quantum Source	Israel
70	QuantWare	Netherlands
71	Qubitcore	Japan
72	Quel	Japan
73	Quemix	Japan
74	QuEra Computing	America
75	Quix	Netherlands
76	QunaSys	Japan

No.	Player Name	Country
77	Quobly	France
78	Rigetti	America
79	Riverlane	United Kingdom
80	SandboxAQ	America
81	SeeQC	America
82	Sigma-I	Japan
83	Silicon Quantum Computing	Australia
84	SpinQ Technology	China
85	Strangeworks	America
86	Tabor Quantum Solutions	Israel
87	TENCENT TECHNOLOGY SHENZEN	China
88	Terra Quantum	Switzerland
89	TOSHIBA	Japan
90	Universal Quantum	United Kingdom
91	XANADU QUANTUM TECHNOLOGIES	Canada
92	XeedQ	Germany
93	Zurich Instruments	Switzerland

Reference: Various public information

Appendix (2) Related Academic Papers

List of Reference Academic Papers 1 and / 4

Industry	Method	Title of the paper	Author	Use Case Overview	Year	peer review status	URL (accessed March 26)
Manufactury	Combination optimisation	Potential Application of Quantum Computing to Automotive Materials Design	Yoshikuni KAN, Akito MARUO, Hideyuki Jitsuho	Application of Digital Annealing to Material Search	2024	peer reviewed	https://www.jstage.jst.go.jp/article/jsaeronbun/55/3/55_20244237/_article/-char/ja/
		Path Planning of Robot Arm Using Quantum Annealing	Arai Shogo, Ito Ryu	Fast Path Planning of Robot Arm Using Quantum Annealing	2024	peer reviewed	https://www.jstage.jst.go.jp/article/jsmermd/2024/0/2024_1P2-L06/_article/-char/ja/
		Simultaneous Optimization of Manipulator Path and Facility Placement in Robotic Cell Production System Using Quantum Annealing	Miwa Shunya, Arai Shogo	Optimization of Manipulator Path and Facility Layout Using Quantum Annealing	2025	peer reviewed	https://www.jstage.jst.go.jp/article/jsmermd/2025/0/2025_2P1-N11/_article/-char/ja/
		Proposal and Prototype of Quantum Inspired In-Vehicle Platform	Koji Oya, Yutaka Fujimoto, Yohei Hamakawa, Masaya Yamazaki, Kosuke Tatsumura	In-Vehicle Architecture Solving Combinatorial Optimization Problems in Real Time	2023	peer reviewed	https://www.jstage.jst.go.jp/article/jsaeronbun/54/6/54_20234535/_article/-char/ja/
Process Manufacturing	Simulation	Dynamics Simulation of Solution Systems by Quantum Classical Hybrid Model	Hiroshi Watanabe	Molecular Simulation of Water Molecules in a Hybrid Model of Quantum Mechanics and Molecular Mechanics	2021	peer reviewed	https://www.jstage.jst.go.jp/article/butsuri/76/2/76_81/_article/-char/ja/
Drug Discovery / Medical Care	AI	Harnessing AI and Quantum Computing for Revolutionizing Drug Discovery and Approval Processes: Case Example for Collagen Toxicity	David Melvin Braga Bharat	Identification of Collagen Drug Toxicity Using Quantum Computation	2025	peer reviewed	https://bioinform.jmir.org/2025/1/e69800/
		Quantum Machine Learning Algorithms for Drug Discovery Applications	Kushal BatraKimberley M. ZornDaniel H. FoilEni MineraliVictor O. GawriljukThomas R. LaneSean Ekins	Quantum Machine Learning Algorithms for Drug Discovery Applications	2021	peer reviewed	https://pubs.acs.org/doi/abs/10.1021/acs.jcim.1c00166
		Quantum AI for Alzheimer's disease early screening	Giacomo Cappiello, Filippo Caruso	Using quantum AI for early screening of Alzheimer's disease	2024	not yet	https://arxiv.org/abs/2405.00755
		The state of quantum computing applications in health and medicine	Frederik F. Flöther	Proof of Concept for Genomics and Clinical Research Quantum Computing	2023	peer reviewed	https://arxiv.org/abs/2301.09106

List of Reference Academic Papers 2/4

Industry	Method	Title of the paper	Author	Use Case Overview	Year	peer review status	URL (accessed March 26)
Drug Discovery / Health Care	Simulation	Bravyi-Kitaev Superfast simulation of electronic structure on a quantum computer	Kanav Setia; James D. Whitfield	Cancer Drug Screening Using Quantum Molecular Simulation	2018	peer reviewed	https://pubs.aip.org/aip/jcp/article-abstract/148/16/164104/196134/Bravyi-Kitaev-Superfast-simulation-of-electronic?redirectedFrom=fulltext
		COVID-19 detection on IBM quantum computer with classical-quantum transferlearning	ERDİ ACAR İHSAN YILMAZ	COVID-19 Detection from CT Images on Classical and Quantum Computers	2021	peer reviewed	https://journals.tubitak.gov.tr/elektrik/vol29/iss1/4/
		A Survey of Quantum Generative Adversarial Networks: Architectures, Use Cases, and Real-World Implementations	Mujahidul Islam, Serkan Turkeli, Fatih Ozaydin	Drug-Target Interaction Prediction Using Quantum Generated Adversarial Network (QGAN)	2025	not yet	https://arxiv.org/abs/2506.18002
		Early quantum computing applications on the path towards precision medicine	Frederik F. Flöther	Healthcare use cases such as genomics and clinical research, diagnostics, therapeutics and interventions	2024	peer reviewed	https://arxiv.org/abs/2403.02733
Finance	Combination optimisation	Backtesting Quantum Computing Algorithms for Portfolio Optimization	Ginés Carrascal; Paula Hernamperez; Guillermo Botella; Alberto del Barrio	Investment Portfolio Optimization with Quantum Computation Algorithms	2023	peer reviewed	https://ieeexplore.ieee.org/abstract/document/10329473
	AI	Application of Quantum Machine Learning and Tensor Networks to Predict Japanese Stock Returns	Nozomi Kobayashi, Yoshiyuki Minato, Koichi Miyamoto, Mitarai Mitsusuke	A Cross-Section Stock Return Prediction Model Using Quantum Neural Networks	2023	peer reviewed	https://www.jstage.jst.go.jp/article/pjsai/JSAI2023/0/JSAI2023_1T5GS202/_article/-char/ja/
		Financial Fraud Detection with Entropy Computing	Babak Emami, Wesley Dyk, David Haycraft, Carrie Spear, Lac Nguyen, Nicholas Chancellor	Financial Fraud Detection by Entropy Computing	2025	not yet	https://arxiv.org/abs/2503.11273
	Simulation	Quantum Computing in High Frequency Trading and Fraud Detection	Adobe Systems, San Jose	High-frequency trading and fraud detection using quantum computing	2021	peer reviewed	https://pdfs.semanticscholar.org/5c94/78db47395fa8b5ddf758f06bb3a9070c86de.pdf
		Comparative performance analysis of quantum machine learning architectures for credit card fraud detection	Mansour El Alami, Nouhaila Innan, Muhammad Shafique & Mohamed Bennai	Credit Card Fraud Detection with Quantum Machine Learning Architecture	2026	peer reviewed	https://link.springer.com/article/10.1007/s10489-026-07110-7
		Fraud detection in credit card transactions using Quantum-Assisted Restricted Boltzmann Machines	João Marcos Cavalcanti de Albuquerque Neto, Gustavo Castro do Amaral, Guilherme Penello Temporão	Fraud Detection in Credit Card Transactions Using Quantum-Assisted Restricted Boltzmann Machine	2025	not yet	https://arxiv.org/abs/2512.17660

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Industry	Method	Title of the paper	Author	Use Case Overview	Year	peer review status	URL (accessed March 26)
Finance	cryptanalysis	Quantum AI for cybersecurity in financial supply chains: Enhancing cryptography using random security generators	Muhammed Azeez,Uyiosa Osarumen Ugiagbe, Ibiso Albert-Sogules, Samuel Olawore, Victor Hammed, Emmanuel Odeyemi, Funmilayo Stacey Obielu and Olayiwola Blessing Akinnagbe	Enhancing Financial Supply Chain Cybersecurity by Integrating Quantum Random Number Generators and Artificial Intelligence	2024	peer reviewed	https://www.researchgate.net/profile/Olayiwola-Akinnagbe-2/publication/382598304_Quantum_AI_for_cybersecurity_in_financial_supply_chains_Enhancing_cryptography_using_random_security_generators/links/686d079c92697d42903dcc75/Quantum-AI-for-cybersecurity-in-financial-supply-chains-Enhancing-cryptography-using-random-security-generators.pdf
Transportation	combinatorial optimization	Applicability of Quantum Computing Technology to Ship Line Design Problems	Kazuhiko Ishiguro, Yoshihisa Sugimura, Tomoya Kawasaki, Kotaro Bannai, Nobutatsu Nakamura	International Maritime Container Route Design Using Quantum Computing Technology	2025	peer reviewed	https://www.jstage.jst.go.jp/article/jscejj/81/18/81_25-18146/_article/-char/ja/
		Qualifying quantum approaches for hard industrial optimization problems. A case study in the field of smart-charging of electric vehicles	Constantin Dalyac, Loïc Henriet, Emmanuel Jeandel, Wolfgang Lechner, Simon Perdrix, Marc Porcheron & Margarita Veshchezerova	Minimizing Smart Charging Weighted Total Completion Time for Electric Vehicles	2021	peer reviewed	https://link.springer.com/article/10.1140/epjqt/s40507-021-00100-3
Energy	combinatorial optimization	Quantum computing in power systems	Yifan Zhou; Zefan Tang; Nima Nikmehr; Pouya Babahajiani; Fei Feng; Tzu-Chieh Wei	Scalable and efficient power grid analysis using quantum computing technology	2022	peer reviewed	https://ieeexplore.ieee.org/abstract/document/9831167
	Simulation	Implementing a Hybrid Quantum Neural Network for Wind Speed Forecasting: Insights from Quantum Simulator Experiences	Ying-Yi Hong, Jay Bhie D. Santos	Wind Speed Prediction Simulation Using Quantum Neural Network Studied by Quantum Simulator	2025	peer reviewed	https://www.mdpi.com/1996-1073/18/7/1771

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Industry	Method	Title of the paper	Author	Use Case Overview	Year	peer review status	URL (accessed March 26)
Other	Combination optimisation	Fundamental Study on Optimal Design of Geotechnical Structures by Quantum Annealing	Takayuki Jukyu, Shinya Yamamoto	Optimal design of pile considering variation of soil parameters using quantum annealing	2022	peer reviewed	https://www.jstage.jst.go.jp/article/jscejge/78/2/78_116/_article/-char/ja/
	cryptanalysis	Quantum-Inspired Sensitive Data Measurement and Secure Transmission in 5G-Enabled Healthcare Systems	Xiaohong Lv The First Affiliated Hospital of Jinzhou Medical University, Jinzhou, China Shalli Rani; Shanmuganathan Manimurugan; Adam Slowik; Yanhong Feng	Measurement and secure transmission of medical data integrating 5G communications, quantum computing, and sensitive data measurement	2025	reviewed	https://ieeexplore.ieee.org/abstract/document/10676360
		Methods and Tools for Secure Quantum Clouds with a specific Case Study on Homomorphic Encryption	Aurelia Kusumastuti, Nikolay Tcholtchev, Philipp Lämmel, Sebastian Bock, Manfred Hauswirth	Strengthening Quantum Cloud Platform Security	2025	not yet	https://arxiv.org/abs/2512.17748
		Exploring Post Quantum Cryptography with Quantum Key Distribution for Sustainable Mobile Network Architecture Design	Sanzida Hoque, Abdullah Aydeger, Engin Zeydan	Quantum Key Distribution for Sustainable Mobile Network Architecture Design	2024	peer reviewed	https://arxiv.org/abs/2404.10602
		Cyber Threat Detection Enabled by Quantum Computing	Zisheng Chen, Zirui Zhu, Xiangyang Li	Cyber threat detection using quantum computing	2025	not yet	https://arxiv.org/abs/2512.18493

(Reference) Research papers covering the past 10 years were searched using keywords such as quantum technology and industry/application.

Research Approach

	dissertation
survey tool	Google Scholar, arxiv
covered period	Last 10 years 2015/2/1 – 2026/1/31
search word	Extraction of documents by And searching ① and② below

① quantum technology

- quantum
- quantum computer
- Quantum computer
- Quantum

×

② industry and application

see the next page

(Reference) Survey using the following extracted keywords for industry and application search terms

② Industry and application search keywords (1/2)

Industry

assembly system

Automobiles
- Automotive
- Vehicle
- Car

aerospace
- Aerospace
- Aircraft Design
- Flight

electronic equipment
- Electronics
- Semiconductor
- Circuit

Robotics
- Robotics
- Automation
- Smart Factories

process system

Chemistry
- Chemical
- Reaction Optimization
- Catalyst Design

Ingredients
- Material
- Material informatics
- Material Discovery
- Nanotechnology

food processing
- Food
- Food
- Food Processing
- Quality Control

petroleum gas
- Oil
- Gas
- Reservoir

Drug Discovery and Healthcare

drug discovery
- Drug Discovery
- Molecular Simulation
- Protein Folding

Medical Care
- Medical Devices
- Imaging Optimization
- Diagnostics

Hospital
- Hospital Management
- Patient
- Personalized Medicine

biotechnology
- Biotechnology
- Genomics
- Bioinformatics

Finance

bank
- Bank
- Banking
- Risk Assessment
- Fraud Detection

Insurance
- Insurance
- Claims Analysis
- Actuarial Science

asset management
- Asset Management
- Portfolio Optimization
- Market Forecasting

Trading
- Trading
- Derivative Pricing
- Market Simulation

Transportation

transportation
- Transportation
- Traffic
- Route

logistics
- Logistics
- Supply Chain
- Warehouse Management

public transportation
- Public Transport
- Scheduling
- Ticketing

air transportation
- Air Cargo
- Flight Scheduling
- Air Traffic Management

Energy

Electric power
- Power Grid
- Energy Storage

renewable energy
- Renewable energy
- Solar
- Wind
- Hydro

atomic energy
- Nuclear Energy
- Reactor Simulation

Energy Efficiency:
- Energy Efficiency
- Carbon Emission Reduction

(Reference) Survey using the following extracted keywords for industry and application search terms

② Industry and application search keywords (2/2)

Method

combinatorial optimization	AI	computer simulation	cryptanalysis
optimisation • Optimization • Search • Combination • Calculation	AI • Artificial Intelligence machine learning • Machine Learning • Deep Learning	CAE/Analysis • Computer-Aided Engineering • Computational Fluid Dynamics • Finite Element Analysis • Simulation • Stress Testing • Fluid Dynamics Design • Design • Structural Analysis • Thermal Analysis	Cyber Security • Cybersecurity • Threat Detection Physical Security: • Physical Security • Surveillance • Biometric Authentication national security • National Defense • Encryption • Secure Communication Cloud Security • Cloud Security • Data Protection • Blockchain

February 17, 2025 (First Edition)
APRIL 15, 2026 (Second Edition)
New Energy and Industrial Technology Development Organization (NEDO)
AI and Robotics Department (e-mail: quantum_ai@ml.nedo.go.jp)

This collection of use cases was obtained as a result of the work commissioned by the New Energy and Industrial Technology Development Organization (NEDO) "Cyber-Physical Development Business of Quantum/Classical Hybrid Technology/Study of Use Case of Quantum Technology" and the ″Post-5G Information and Communications System Infrastructure Reinforcement R & D Project (Quantum Industrialization)/Comprehensive Study for Promoting the Industrialization of Quantum Computers″.