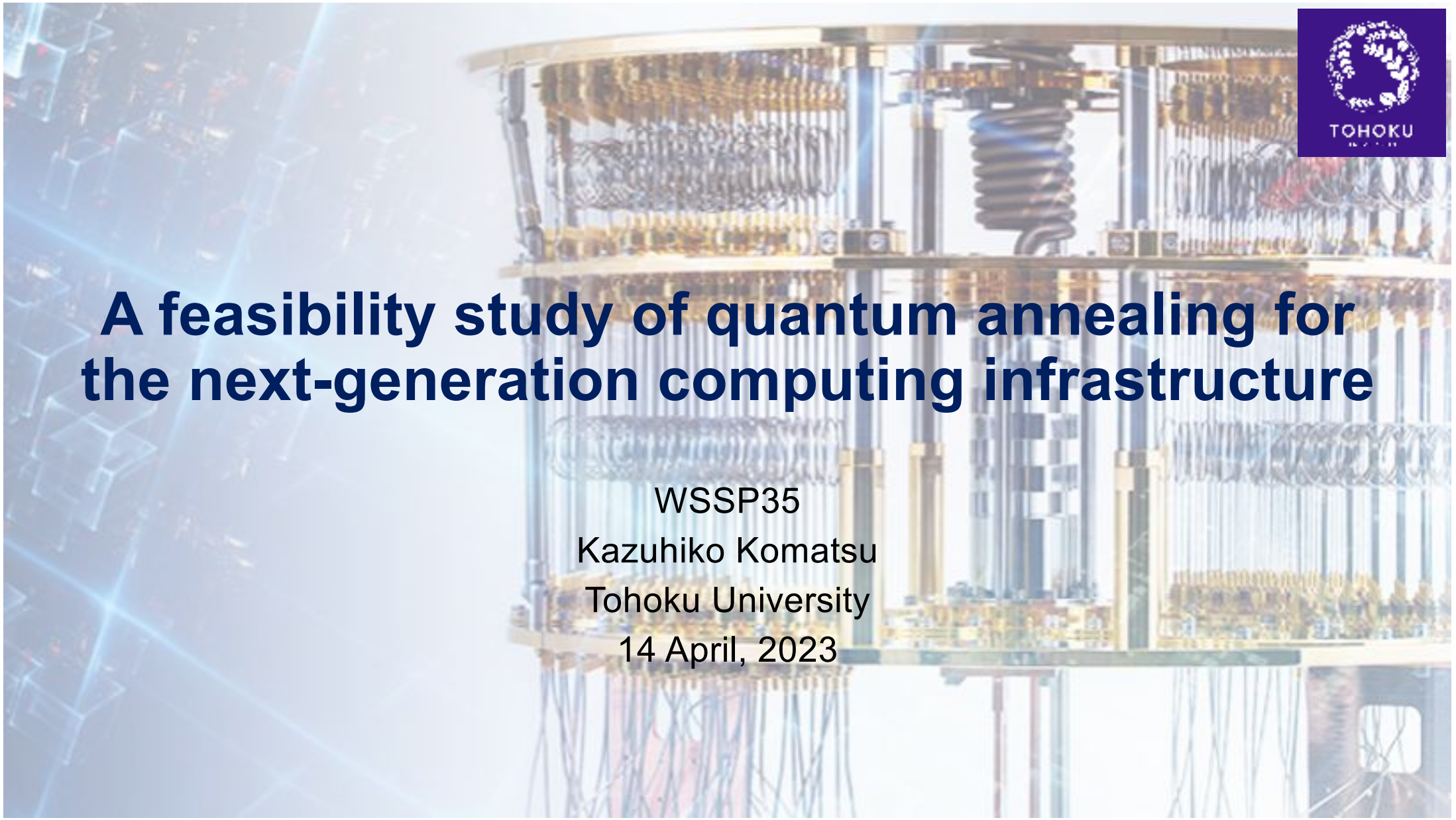

A feasibility study of quantum annealing for the next-generation computing infrastructure

WSSP35

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Tohoku University

14 April, 2023

Agenda

Introduction of feasibility study of quantum computing

- Quantum annealing group by NEC and Tohoku Univ.

Evaluation of annealing machines

- Ongoing investigations are yielding preliminary findings

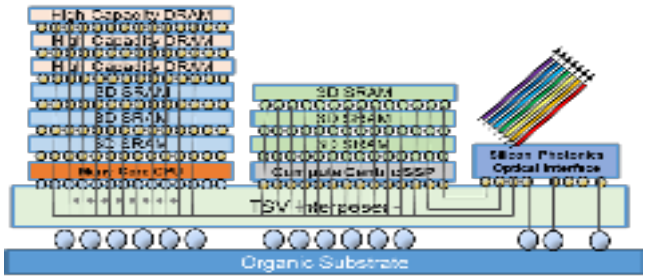
Feasibility studies (2022/08~2024/03)

Overview

- R&D of essential technologies to develop the next-gen. computing infrastructure

System team

- Architecture
- System software
- applications

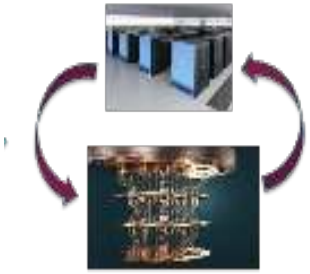


Operation technology

- Operation-related technologies

New computational principles

- Quantum supercomputing
  - Hybrid computing by QC, QA, SC

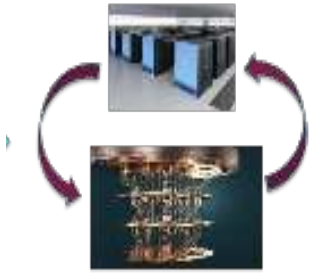


supercomputer

Quantum computer

FS of new computational principals

supercomputer

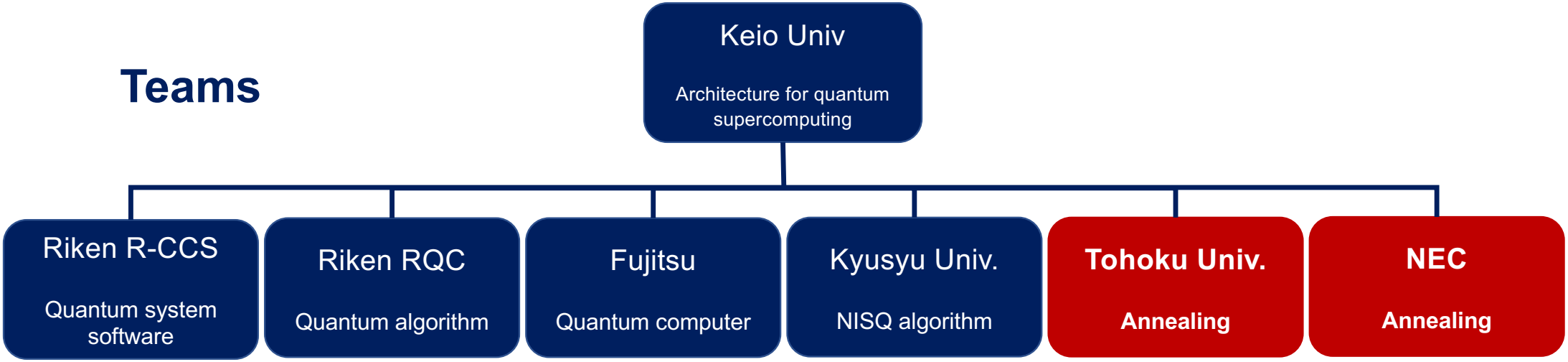


Quantum computer

Overview

- Evaluate the feasibility of "**quantum supercomputing**" by hybrid computing of HPC and quantum computing
  - Study on architecture, system software, and algorithms of quantum supercomputing

Teams



Quantum Annealing Group

Feasibility study on quantum / simulated annealing machines

- Performance evaluation using various annealing machines
- Evaluation matrix regarding quantum annealing machines

The last fiscal year

- Survey of annealing machines and evaluation methods
- Experimental environments for performance evaluation
  - NEC, D-wave, Fujitsu, Toshiba, Hitachi, Fixstars, etc
  - Developments of benchmark programs

Schedule of this fiscal year

- Evaluation metrics

	2022 fiscal year			2023 fiscal year	
	8～9	10～12	1～3	First half	Second half
Annealing (Tohoku U・NEC)	Survey of QAs and SAs	Evaluation of QAs and Sas	Analysis of the evaluation results	Clarification of evaluation metrics and performance requirements	

Quantum Annealing teams

○Representative

Tohoku university
Kazuhiko Komatsu

Quantum future society vision
Quantum technology innovation office
Quantum solution

Cyberscience Center

○Kazuhiko Komatsu

Mitsuo Yokokawa

GSIS

☆Masayuki Sato

NEC

○Shintaro Momose

Hiroshi Chishima

☆Bannai Kotaro

Overview

Introduction of feasibility study of quantum computing

- Quantum annealing group by NEC and Tohoku Univ.

Evaluation of annealing machines

- Ongoing investigations are yielding preliminary findings

Recent quantum-related activities

Quantum system architecture

- Understanding the characteristics of quantum computing
  - Clustering, TSP, QAP, MIS
- Optimization techniques for quantum computing
  - Constraint weight partitioning
- Investigation of evaluation methods and metrics for quantum computing

Quantum algorithms

- Development of algorithms utilizing quantum computing
  - Ising-based machine learning such as clustering and regression.

Quantum applications

- Development of Applications utilizing quantum computing
  - Material segmentation, Failure detection of turbine, tsunami evacuation planning

Quantum startup

- Sharing economy using quantum computing

Varieties of annealing machines

Types of annealing machines

- Quantum annealing
  - Analog circuits with quantum effects
    - QA using superconducting quantum circuit by D-Wave Systems, Inc
- Simulated (Quasi-quantum) annealing
  - Use of digital processors such as CPU, GPU, and VE
    - D-wave Neal, Fixstars Amplify Engine, Vector Annealer, and so on
- Digital annealing
  - Dedicated digital circuits such as CMOS and FPGA
    - Hitachi CMOS Annealer, and so on

Different features and performance by rapid developments

Annealing machines

Machines	Hardware	Max # bits	# bits fully	Connectivity	Bit precision	Services
D-wave 2000Q	Quantum circuit	2048	64	Chimera graph	Analog 5 bits	Cloud
D-wave Advantage	Quantum circuit	5,760	124	Pegasus graph	Analog 5 bits	Cloud
D-wave Advantage2 Proto	Quantum circuit	563		Zephyr graph	Analog 5 bits	Cloud
D-wave Leap Hybrid	Quantum + digital circuit	N/A	N/A	N/A	N/A	Cloud
D-wave Neal	CPU	N/A	N/A	Fully	Digital 64 bits	Local
NEC Vector Annealer	VE Type 20B	100,000+	100,000+	Fully	Digital 32 bits	Local
Fixstars Amplify Engine	Nvidia A100	262,144	131,072	Fully	Digital	Cloud
Hitachi CMOS Annealer	GPU	61,952	176	King graph	Digital 3bits	Cloud
Toshiba SQBM+	GPUs	10,000,000	10,000,000	Fully	Digital	Cloud

Benchmarks

Clustering

- Clustering using the Ising model

TSP (Travel Salesperson Problem)

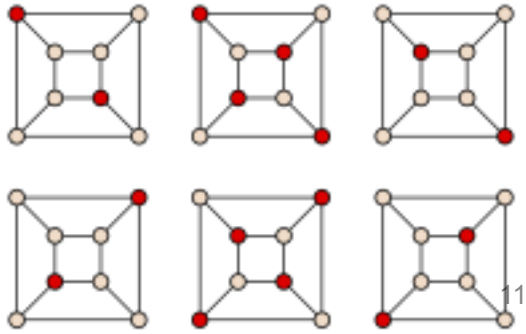
- Well-known NP-hard combinatorial optimization problem
- Find the shortest route that a salesperson can take to visit given cities exactly once and return to the starting city

QAP (Quadratic Assignment Problem)

- A combinatorial optimization problem often used as a benchmark
- Find the assignment that minimizes the sum of the products of flows and distances between all pairs of assigned facilities and locations when a set of n facilities and n locations

MIS (Maximum Independent Set)

- Find the largest possible independent set in a given graph, where no two vertices in the set are adjacent



Evaluation metrics

TTS(Time to solution)

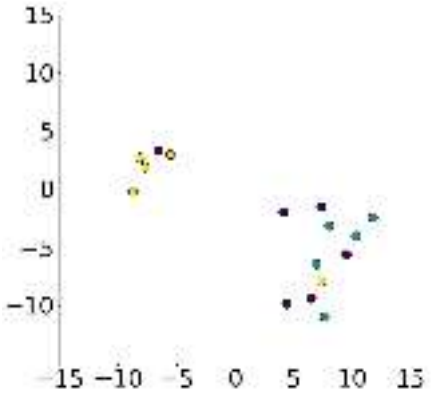
- Execution time to reach the lowest solution found
  - $\mathrm{TTS} = \gamma_{anneal} R + T_{others}$
    - γ_{anneal} : Annealing time
    - R: Annealing times to obtain the reference solution $R = \frac{In(1-p_R)}{In(1-p_{success})}$
    - T_{others}: Time for the other than annealing such as QUBO generation

Objective value

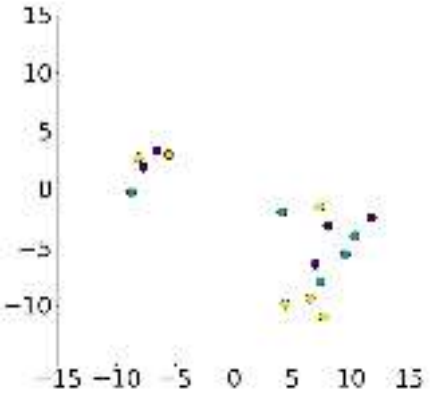
- Clustering: sum of distances within the same cluster for all clusters
- TSP: total distance traveled
- QAP: workload
- MIS: number of independent sets

Execution time

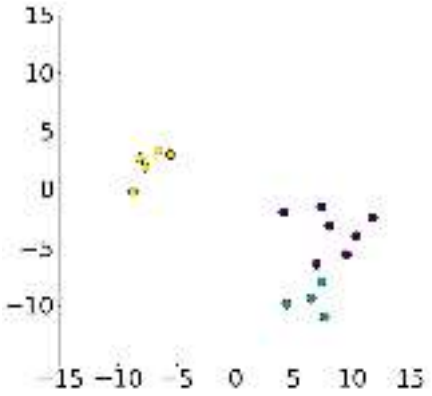
Clustering: visualization results



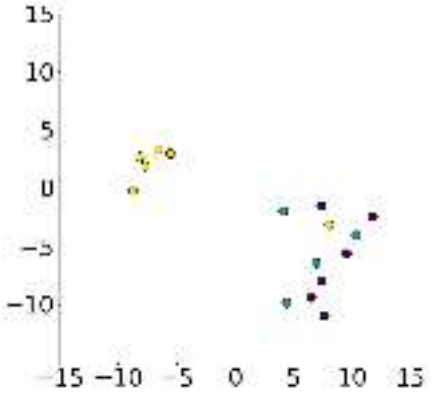
D-wave 2000Q



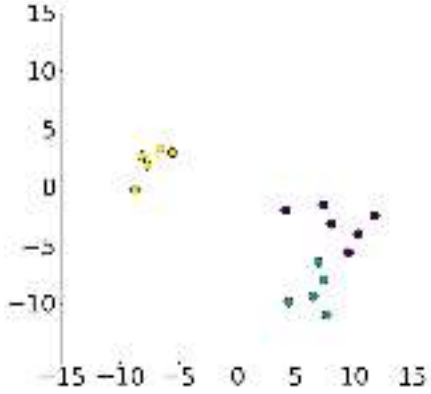
D-wave Advantage



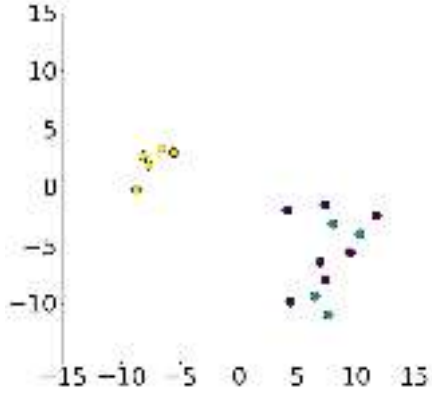
D-wave Leap Hybrid



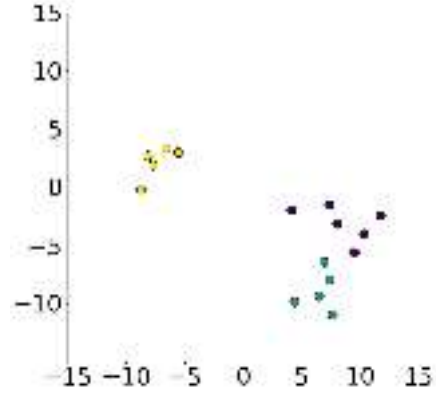
D-wave Neal



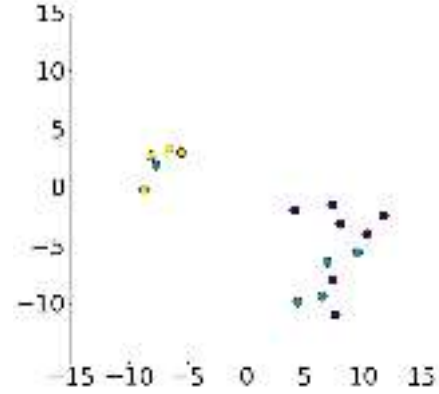
NEC Vector Annealer (External)



NEC Vector Annealer (Internal)

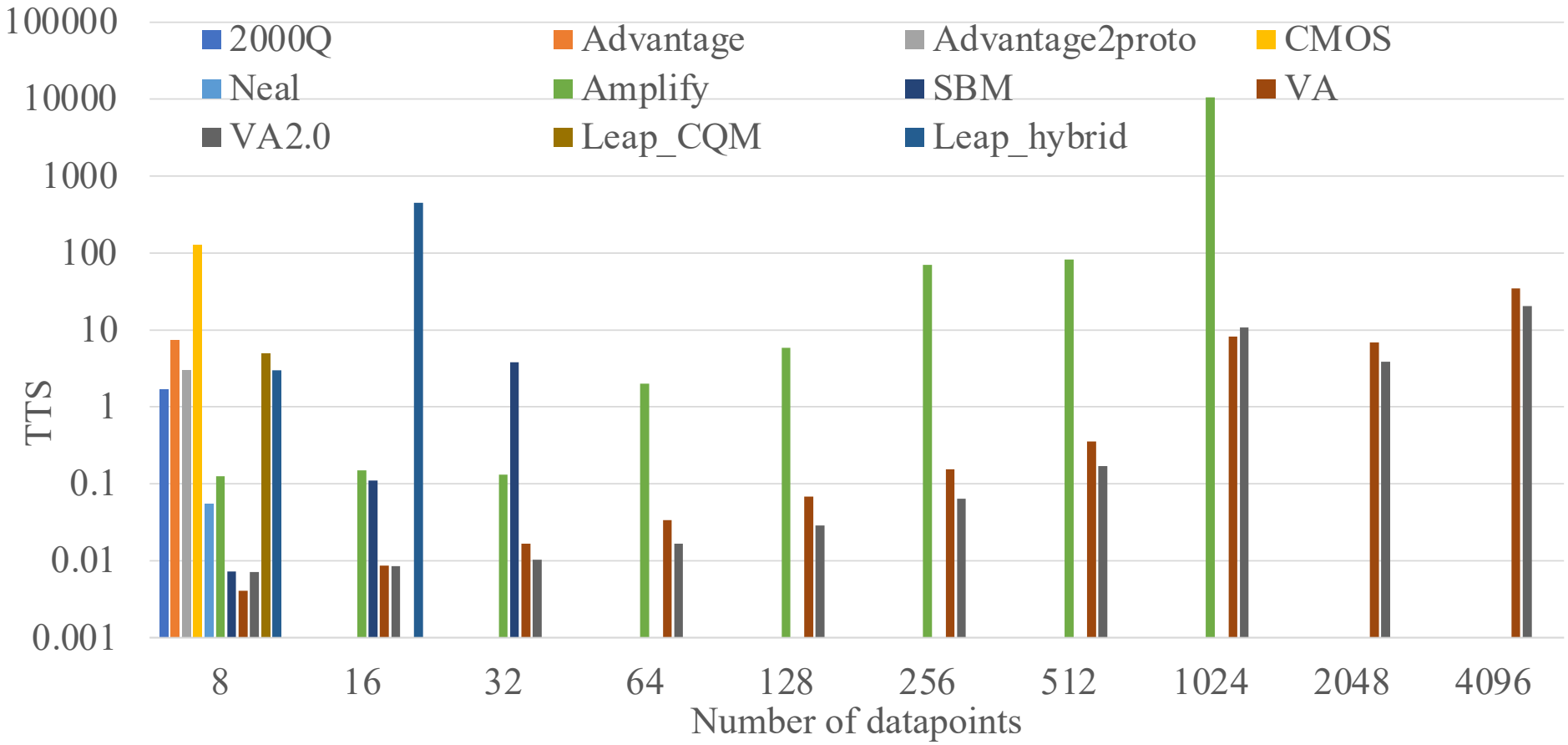


Fixstars Amplify Engine

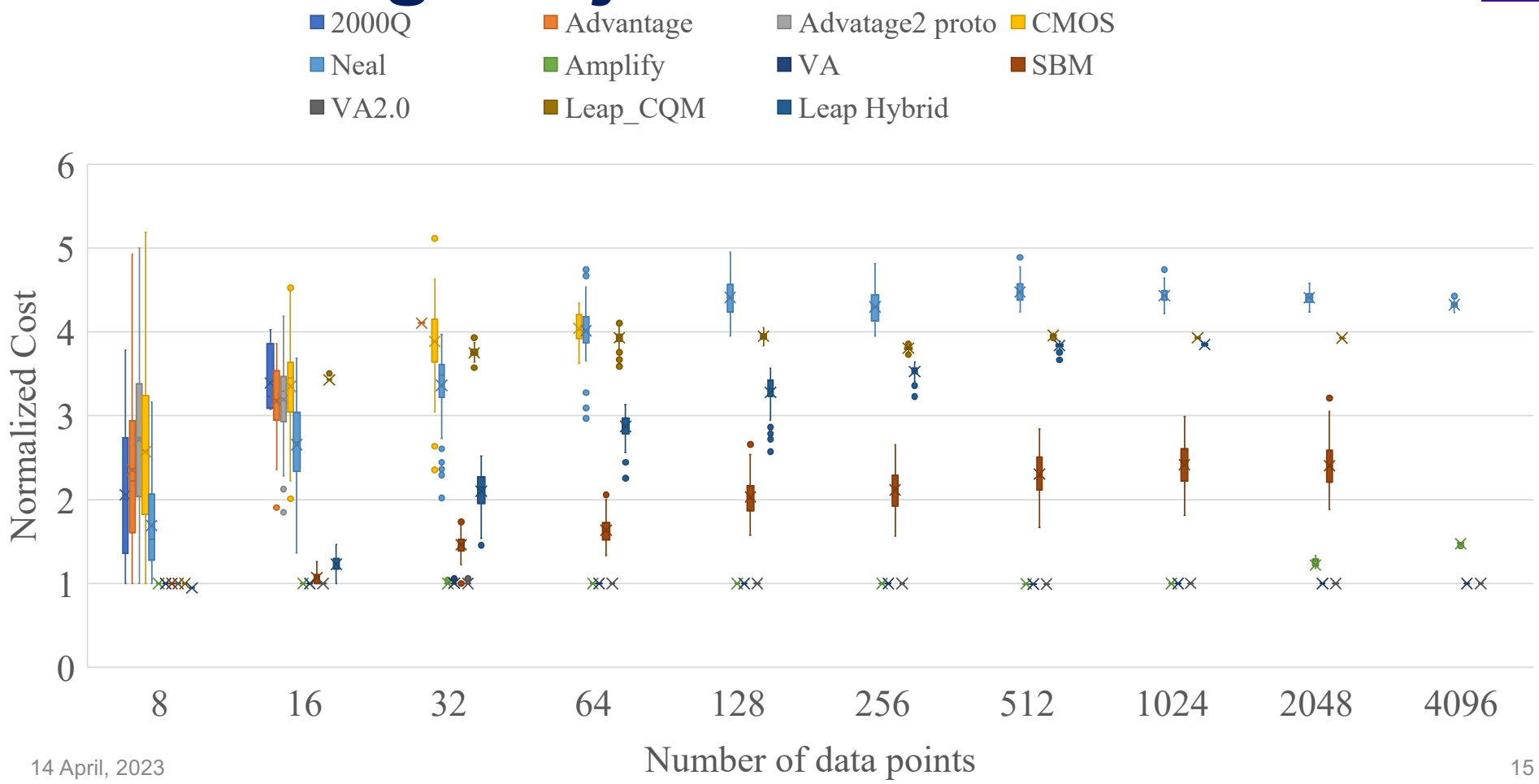


Hitachi CMOS Annealer

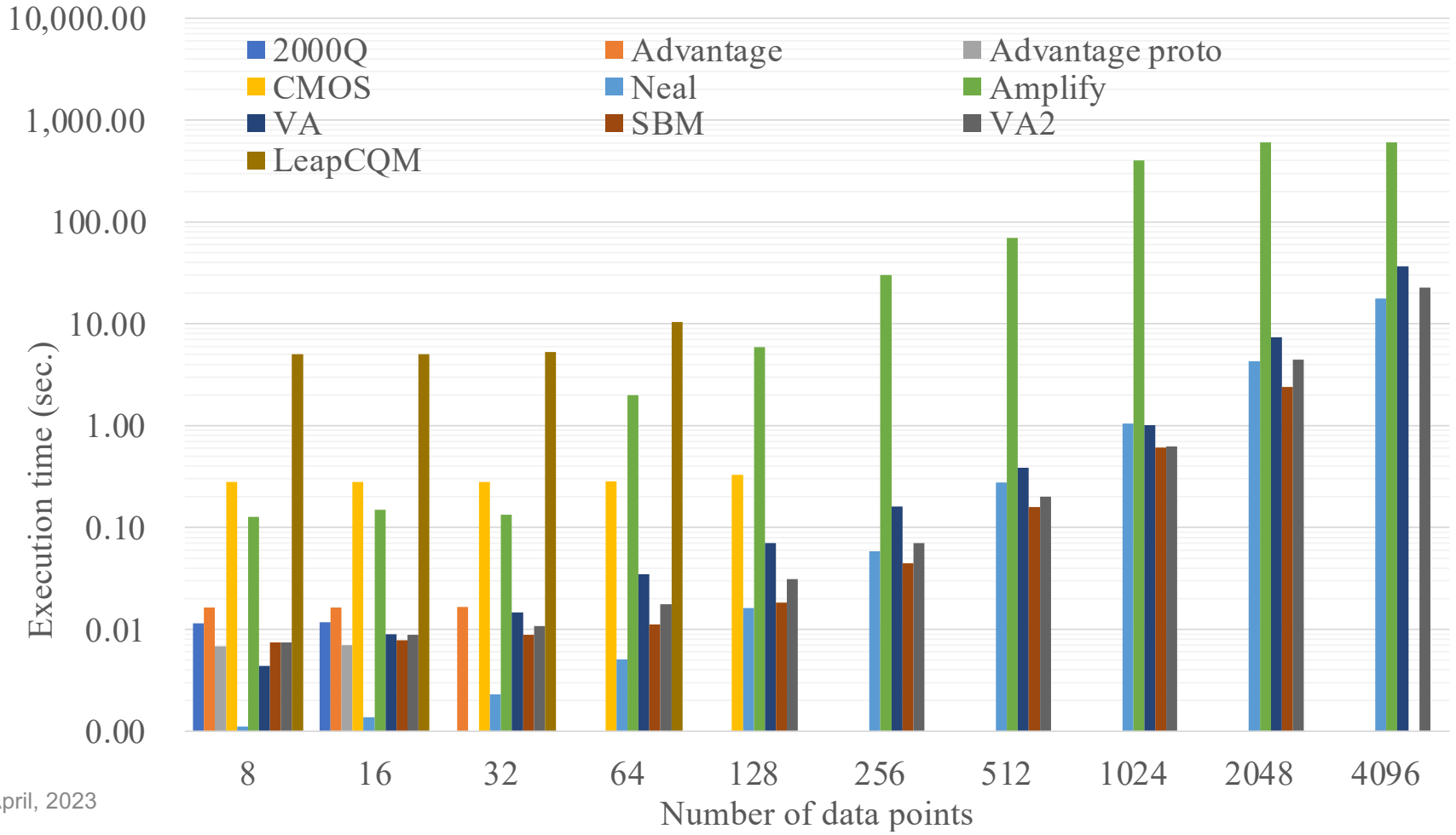
Clustering: TTS



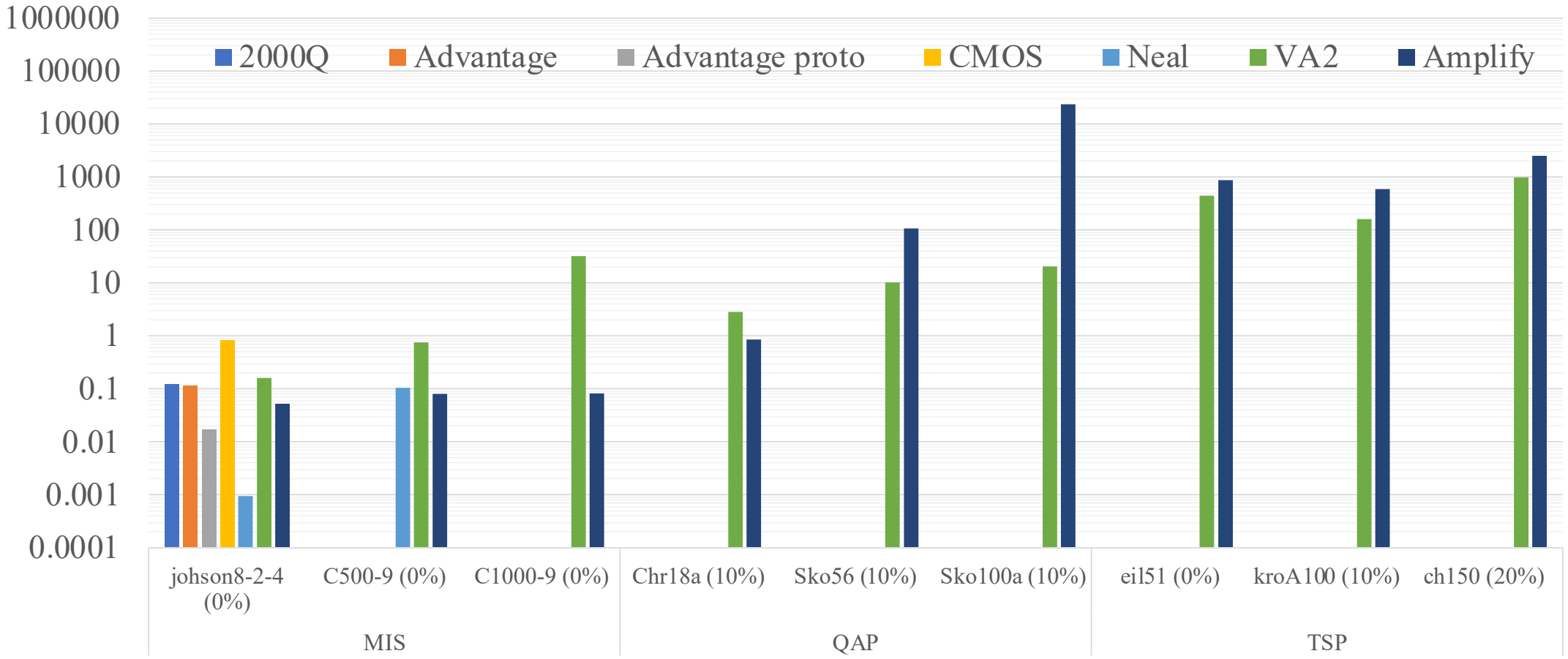
Clustering: Objective value



Execution time



MIS, QAP, TSP: TTS



Conclusions

From performance evaluation of various annealing machines

- The suitable annealing machine depends on an application
  - Vector Annealing is suitable for clustering, QAP, TSP
    - These benchmarks may place greater emphasis on constraints than on the objective function?!
  - Fixstars Amplify engine for MIS
    - The objective function may be important rather than the constraints?!

To establish performance metrics for quantum computer

- It is necessary to conduct further investigation into factors that contribute to differences in performance