Quantum Computing Algorithms for optimised Planning & Scheduling (QCAPS)

Qubits Europe 2019 conference

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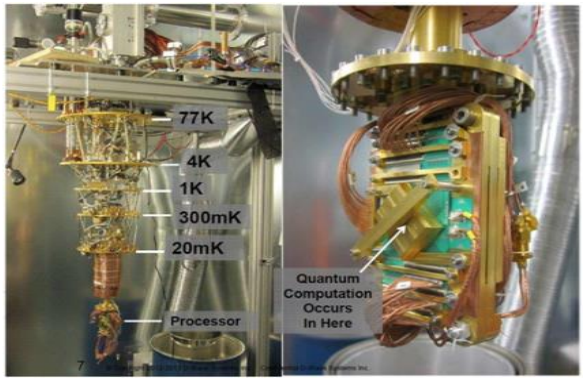
QCAPS Quantum computing algorithms for optimised planning/scheduling

InnovateUK task (£400k task 12 months Oct 2017-Oct 2018)

Plantagenet SYSTEMS · BT · UCL · University of BRISTOL · D:Wave The Quantum Computing Company™

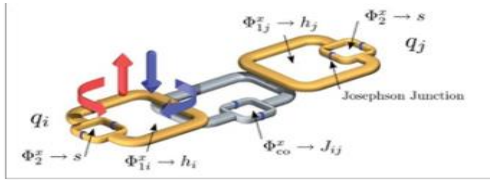
Premise

- Existing techniques can be enhanced by quantum algorithms to deliver optimised plans/schedules in real-time for complex tasks
  - Processing power may be increased by several orders of magnitude
  - When could this happen? How large a quantum processor is required?



Technical feasibility

- Perform initial experiments with quantum annealing (D-Wave)
- Explore how/where universal quantum algorithm could realise further gains in optimised planning applications



Business Feasibility

- Explore use cases within telecoms optimisation/job-shop scheduling
- What other business/market applications will benefit?

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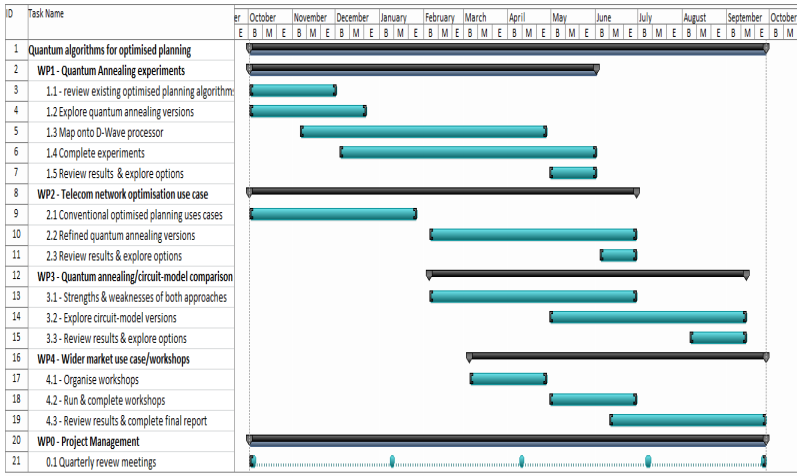
Work packages – quantum algorithms for optimised planning/scheduling

WP1: Quantum annealing experiments

- Reviewed existing AI planning algorithms for benchmarking
- Explored options for enhancing using quantum annealing
- Mapped algorithms onto D-Wave processor and run experiments



WP2: Telecom network optimisation use cases

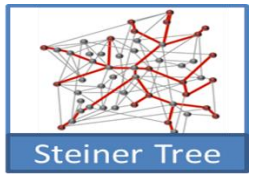
- Identified candidates for telecom network optimisation
- Re-ran experiments and explored speedup/scaling issues

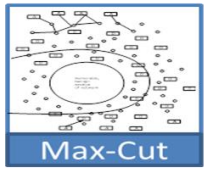
WP3: Comparison quantum annealing vs gate-model approaches (universal)

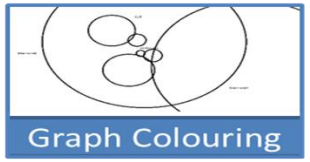
- Performed theoretical analysis of improved speedup/scaling for gate-model approaches
- Explored strength/weakness of both quantum computing approaches

WP4: Business feasibility for optimisation tasks

- Organised market-focussed innovation workshop, inviting key industry/market players
  - Distribution logistics/traffic-flow optimisation
  - Telecom network optimisation
  - Operations management (Manufacturing/Infrastructure/Military)







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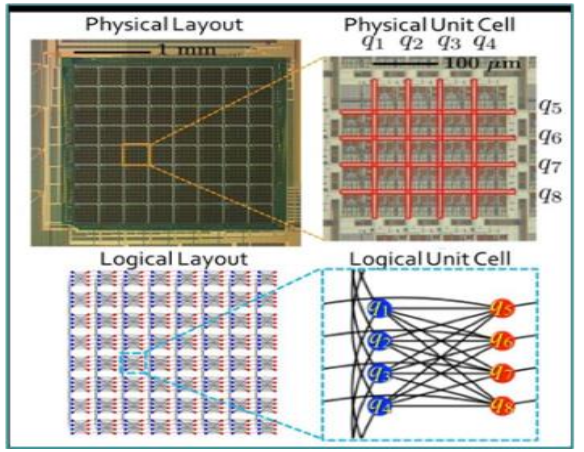
WP1/2 Experiments – Mapping onto D-Wave processor

Transforming job-shop scheduling tasks into QUBO formalism

- Currently require strong mathematic background to generate QUBOs
  - Key issue is characterising constraints within QUBO formalism
  - As more constraints added, QUBO formalism becomes more complex
- Libraries of QUBOs would help non-mathematicians to represent JSPs

Mapping onto D-Wave processors

- Allocating physical qubits vs logical qubits
  - Minimising chains of physical qubits to represent logical qubits
  - Allocating weights and coupling strengths to individual qubits
- D-Wave provide software for
  - Mapping qubits and setting weights/coupling
  - `qbsolv` algorithm for larger scheduling problems



Opportunities for quantum annealing software

- Which parts should be left classical, which quantum
  - Classical: manage global search trees, check validity/quality of candidate solutions
  - Quantum: sampled from problem space, guide exploration/pruning of search trees

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WP1/2 Quantum annealing experiments – Achievements

Reviewed several types of optimised planning/scheduling tasks

- Confirmed quantum annealing better suited to optimised scheduling, rather than planning
- Complexity of optimised planning requires power of universal quantum computing algorithms

Performed quantum annealing experiments for JSPs and telecoms network optimisation

- Explored key factors in mapping onto annealers and where best to apply quantum to hybrid solutions
- Explored largest size tasks addressable by DW2000Q and benchmarked against Google OR-tools
  - DW2000Q cannot address hard JSPs, needs 10^9 physical qubits with existing chimera topology (6x connectivity)
  - For half-duplex mesh problems, needs 300,000 physical qubits for national scale (50,000 cells)
  - Annealing generates near-optimum solutions after few anneal, even for large problems

Determined what needs to be done to address hard JSPs/telecoms use cases

- Improved vertex connectivity is more challenging than increasing number of qubits (Next Gen)
- Libraries of QUBOs would help non-mathematicians to represent hard problems
- Improved software for mapping qubits and setting weights/coupling

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WP3 Optimised planning/scheduling using universal QC

Existing quantum algorithms

- Not all quantum algorithms relevant for optimisation problems
- Most deliver quadratic speedup, rather than exponential

Known (square-root, provable) quantum speedups include:

- Unstructured combinatorial search / optimisation
- Backtracking (trial and error)
- Monte Carlo methods for parameter estimation

A quantum speedup is **unlikely** to be achievable when:

- The algorithm needs to operate on large amounts of data
- There is already a fast classical competitor

Determining whether a theoretical quantum speedup is actually achieved in practice can be a significant challenge!

WP3 – Universal (gate-model) approaches versus quantum annealing

Reviewed several quantum algorithms (gate-model) for planning/scheduling

- Emphasised algorithms with rigorous performance/correctness guarantees
- Graph colouring problems good for representing optimised scheduling tasks

Provided detailed complexity analysis for quantum backtracking (graph colouring)

- Analysis proves backtracking algorithm outperforms classical processor (specific scenarios)

Comparison of gate-model versus quantum annealing approaches

	(universal) gate-model	quantum annealer
Applications	Optimised planning and scheduling	Optimised scheduling only
Speedup	Sometimes provable	Certified experimentally
Hardware required	Graph Colouring 10^6 logical qubits 10^{13} physical qubits	Graph Colouring (10,000-50,000 cells) (National) $3x10^5$ physical qubits (chimera) (City-wide) $6x10^4$ physical qubits (chimera)
Availability	15-20 years	8-15 years
	10-15 years (improved fault tolerance)	5-10 years (improved connectivity)
	>10 years (near optimal/relaxed quantum advantage)	3-5 years (near optimal/relax quantum advantage)

WP4 Business feasibility for optimisation – Achievements

Engaging with key stakeholders

- Held innovation workshop with 50+ participants
  - Potential end-users, quantum experts (academia/industry/fund-holders)
- Provide update on current experiments and other case study applications
  - Use case: Telecoms network optimisation (BT)
  - Use case: Traffic flow optimisation (VW)
  - Use case: Distribution Logistics (Ocado)

Characterised major business applications

- Identified range of practical optimisation problems across 3 market sectors
  - Questionnaire covering top 20 questions (technical/business feasibility), including major enablers and barriers to introduction in key markets

Market assessment for optimised planning and scheduling tasks

- Defined potential global market size for hybrid solutions over next 5-10 years
- Supply-chain opportunities for UK business for hybrid solutions/services
- Roadmaps for pragmatic capability development

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WP4 Innovation workshop – Brainstorming outputs

Team1 : Telecoms

- Traffic engineering
  - Quality of service
  - Routing/spectrum management
  - Batching streams & content
- Traffic monitoring
  - Feature analysis/pattern ID
  - Deep packet inspection (DPI)
  - Applications of machine learning
- Resource scheduling
  - Workforce optimisation
  - Network operations/maintenance
- Topology design
  - Infrastructure layout design
  - Location of base stations/masts

Team2: Distribution

- Distribution logistics
  - Vehicle routing (trunk/local networks)
  - Warehousing/supply depots
  - Logistics scheduling (strategic/tactical)
- Traffic-flow optimisation
  - Vehicle flow optimisation(cars/trucks)
  - Rail network optimisation
  - Maritime traffic management
  - Air traffic management/control
- Maintenance scheduling
  - Predictive maintenance
  - Staff resource allocation
  - Automated manufacturing

Team3: Operations

- Scheduling operations
  - Hospital planning
  - Fleet/inventory management
  - Airport/flight scheduling
  - Military operations
  - Power/grid management
  - Oil/gas (upstream/downstream)
- Strategic decision-making
  - Drug discovery/development
  - Materials modelling
  - Cancer screening/food standards
  - Met Office forecasting
- Supply chain optimisation
  - Infrastructure management (cities)
  - Urban transportation networks
  - Critical national infrastructure (CNI)
- Operational resilience
  - Managing data deluge (IoT)
  - Understanding daily threats
  - Managing critical nodes (global)

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WP4 Business feasibility – Market assessment

Global market for hybrid solutions	Hybrid (overall) date	Hybrid (overall) date
Telecoms network optimisation	$1.6Bn ($31.8Bn) 2023	$6.9Bn ($46.4Bn) 2028)
Distribution logistics	$0.97Bn ($19.4Bn) 2021	$4.9Bn ($32.9Bn) 2026
Traffic-flow optimisation (land/air/sea/rail)	$1.4Bn ($28.1Bn) 2022	$12.7Bn ($84.8Bn) 2027

Assumption: Hybrids solutions/services at 5% overall market size(2021-23) and 15% (2026-28)

Roadmap: Capability development

- Quantum annealing: optimal scheduling 8-15 years
  - Improved connectivity/near optimal/relaxed quantum advantage: 3-5 years
- Universal (gate-model): optimal planning/scheduling 15-20 years
  - Improved fault tolerance/near optimal/relaxed quantum advantage: >10 years
- Other factors affecting emergence of hybrid solutions
  - Strongly integrated hybrid quantum classical systems/solutions
  - SWAP benefits of quantum processors

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Opportunities for UK plc

Hardware & Systems

- Specialist quantum processors (e.g. D-Wave, IonQ)
- Hybrid quantum/classical system engineering (Design/Test/Integration)
- Supply chain components (photonics, cryostat) (e.g. e2V, M2Lasers, Oxford instruments)

Software

- Compilers, Code optimisers (e.g. CQC)
- Algorithms and Programming languages (e.g Riverlane Research)
- Libraries of quantum designs

End-users organisations & specialist groups

- Finance, Transport, Logistics, Telecoms, Energy, Manufacturing, Defence/Security
- Specialist consulting orgs (e.g. 1QBit, QxBranch, QCware)

Academia

- Continued development of science, technology and systems engineering
- Training the next generation of quantum experts & practitioners

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Summary of achievements – Quantum algorithms for optimisation problems

WP1: Quantum annealing experiments

- Confirmed quantum annealing better suited to optimised scheduling, rather than planning
- Performed quantum annealing experiments for JSPs (mapping/hybrid solutions)
- Determined how to address hard JSPs (increase connectivity/number of qubits)

WP2: Telecom quantum annealing experiments

- Characterised several hard problems in telecoms network optimisation
- Performed quantum annealing experiments on half-duplex mesh network and FAP problems
- Highlighted size of processor required to address key telecoms industry problems

WP3: Optimised planning/scheduling using universal(gate-model) approaches

- First detailed comparison different quantum approaches (gate-model versus annealing)
- Confirmed number of logical/physical qubits for graph colouring for both approaches
- Outlined technology roadmap for addressing (industry-scale)optimisation problems

WP4: Business feasibility for optimisation

- Engaged with key quantum stakeholders and characterised several business applications (3 market sectors)
- Provided a detailed market assessment (market size, UK opportunities/roadmaps for early adoption)

Delivered thorough technical/business feasibility study of hybrid solutions for optimised planning/scheduling tasks in three market sectors

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