Exploration of the Potential of Quantum Annealing for Hard Scheduling Problems in Air Traffic Management

Introduction

Quantum annealing is a metaheuristic for solving computationally challenging combinatorial optimization problems. While its power is unproven, there are strong scientific reasons to expect that it will give an advantage over classical methods for certain optimization problems through its use of inherently quantum phenomena, such as tunneling and entanglement, to traverse the landscape of solutions more effectively. Early-stage quantum annealing hardware has become available in the last few years and has been advancing quickly. The state-of-the-art D-Wave 2X quantum annealer, containing the Washington chip, is hosted at only two locations in the world: NASA Ames and D-Wave Systems, Inc.

The objective of the proposed work is to seed an effort to explore the potential of quantum annealing for computationally challenging problems within Air Traffic Management (ATM). Our past work in the planning domain[1,2] suggests that scheduling problems are amenable to quantum annealing approaches. In this work, we will develop and evaluate specialized quantum annealing approaches for tackling a variety of scheduling problems of interest to NASA within the area of ATM. The output of the proposed work will be an analysis of two specific types of ATM scheduling problems and the development of a general research strategy including an assessment of promising near-term research directions.

Approach

Quantum annealing can be applied to any discrete optimization problem. The constraints of state-of-the-art hardware limit the size of problems that can be attempted, so efficient compilation approaches are critical, as is the choice of initial problems to explore. Our proposed research in the ATM domain will leverage our experience with quantum annealing for automated operational planning[2], which included an evaluation of quantum annealing approaches to a class of simple scheduling problems. Within the ATM domain, we will target the many computationally hard optimization problems that contain elements of combinatorial challenges derived from resource allocation, job-shop-scheduling, and queuing theory. Components of our approach include:

Problem identification: Identify suitable types of problems within the ATM domain for initial evaluation, with emphasis on optimization problems that benefit from a diversity of valid solutions. Through discussion with ATM experts, we have already identified one suitable type: finding distinct minimum-cost configuration scheduling advisories (CSAs). Other problems that will be considered include the optimization of near-terminal landing sequences in airports, and the taxiing of aircraft after landing. We will work with domain experts at NASA and at Stanford to identify other types of problems for evaluation.

Specialized quantum annealing algorithm development: Design novel mappings of ATM scheduling problems to quantum annealing and specialized compilation techniques suitable for the D-Wave 2X architecture and that of other expected near-term quantum annealers. The CSA requirement for diverse solutions will spur the development of the first quantum annealing approaches aimed at returning a diverse set of solutions, enabling the exploration of a conjectured advantage of quantum annealing due to its unique sampling properties.

---

[1] Quantum Annealing Implementation of Job-Shop Scheduling, D. Venturelli, D. J. J. Marchand, G. Rojo, http://arxiv.org/abs/1506.08479

[2] A case study in programming a quantum annealer for hard operational planning problems, E. G. Rieffel, D. Venturelli, B. O'Gorman, M. B. Do, E. M. Prystay, V. N. Smelyanskiy, Quant. Inf. Process. 2015, Volume 14, pp 1-36; Compiling Planning Into Quantum Optimization Problems: A Comparative Study, B. O'Gorman, E. Rieffel, M. Do, D. Venturelli, J. Frank, ICAPS-15 (COPLAS workshop)

Establish benchmark problem sets: The D-Wave 2X housed at NASA Ames has 1,097 qubits, which means problems must have fewer than 1097 binary variables for a pure quantum annealing approach, but problem decomposition methods can enable the tackling of larger problems. The limited connectivity of 3,060 couplings between the qubits further limits the problem size. A critical step in our evaluation is the design of benchmark problem sets that capture the essence of the ATM problems of interest and on which scaling analysis can be done.

Computational experiments and analysis: Run the specialized algorithms on the D-Wave 2X quantum annealer, evaluating their performance on the designed benchmark sets.

Technical details on potential initial target problems

Minimum cost CSAs. A promising candidate problem is that of finding distinct minimum-cost configuration scheduling advisories (CSAs)[3,4]. Solutions to this problem provide air traffic controllers with fast, high-quality decision-support tools while enabling them to use their judgment to account for aspects of the situation not captured by the mathematical model. A configuration scheduling advisory is a time-dependent grouping of airspace sectors and assignment thereto of workstations and controllers in an air traffic control center. Much fieldwork has been done to construct an appropriate cost-function that balances such factors as the workload of operators, the availability of workstations, the density of aircraft in different sectors, and the costs of changing different parts of the configuration. The value of producing several distinct CSAs for the controller to choose from is two-fold: first, it enables the controller to use his or her intuition to account for soft factors unable to be accounted for in even the best quantitative model, and second, it enables the controller to use information that was intentionally omitted from the model for non-computational reasons, such as the relative strengths or weaknesses of individual operators. Our experience applying quantum annealing to real-world problems leads us to believe that the distinct CSAs problem is an excellent candidate for exploring the utility of quantum annealing in producing diverse solutions. Not only is there practical utility in having diverse solutions, the problem's structure is conducive to efficient mapping: it has a discrete, parametrizable solution space, with a low-resolution energy spectrum. Importantly, small-scale instances of this problem are used in practice.

ATM problems that map to Job Shop Scheduling. Various ATM problems such as optimizing near-terminal landing sequences are directly mappable into variations of Job Shop Scheduling (JSP)[5]. Our team has recently implemented a quantum annealing-based solver for JSP problems[1]. A promising research strategy is to adapt and improve this prior work to the ATM case. Preliminary investigations of runway scheduling problems suggest that simplified real-world cases (e.g. scheduling of fewer than 10 aircraft within 30 minutes) could be programmed and run on the new D-Wave 2X system, with the objective being to extrapolate the performance estimates to larger problems. Such problems are not far from the state-of-the-art classical limits; optimal solutions of JSP with as little of 15-20 machines (aircraft, for ATM purposes) are extremely challenging if not unattainable by standard methods.

Assessment

We will rely on a variety of performance metrics to assess the efficiency of the algorithms to find optimal or near-optimal solutions and on metrics of solution diversity. The best means to assess performance

---

[3] Advisory Algorithm for Scheduling Open Sectors, Operating Positions, and Workstations, Michael Bloem, Michael Drew, Chok Fung Lai, and Karl D. Bilimoria. Journal of Guidance, Control, and Dynamics 2014 37:4, 1158-1169

[4] M. Bloem and N. Bambos, "Air Traffic Control Area Configuration Advisories from Near-Optimal Distinct Paths," AIAA J. of Aerospace Information Systems, Vol. 11, No. 11 (2014) http://arc.aiaa.org/doi/abs/10.2514/1.I010219

[5] Scheduling models for air traffic control in terminal areas, L. Bianco, P. Dell'Olmo, S. Giordani, Journal of Scheduling 2006, vol 9 pp 223;

depends on the problem, but we will use standard efficiency metrics (e.g. median time-to-solution) with particular interest in the scaling as the problem size grows. As a side benefit of this research, more sophisticated metrics for the diversity of solution may be developed that would be of interest generally for assessment of advice tools in human-in-the-loop settings.

Innovations in quantum annealing architectures over the next decade are not easily predictable, presenting one challenge for this technology area. The expectation is that this work will guide the design and operation of the next generation of quantum annealers, enhancing their ability to solve application problems of NASA interest. An assessment of high near-term potential impact of quantum annealing in the ATM domain could lead to special-purpose quantum annealing hardware aimed at such problems.

Description of the team

NASA's Quantum AI Laboratory (QuAIL) is an internationally recognized leader in quantum computation, particularly in the exploration of quantum annealing applications and programming techniques. We have developed quantum-annealing algorithms for applications in domains such as fault detection[6], planning, and scheduling. QuAIL scientists have unmatched experience in benchmarking and programming quantum annealers since D-Wave's release of the first 128 qubit chip in 2012[7]. The proposed effort will benefit from our on-going research efforts in advanced device calibration[8], noise-cancellation and program compilation methods[9], and the physics of quantum speedup[10]. We work closely with researchers at MIT Lincoln Laboratory, ETH Zurich, and Texas A&M as part of the most ambitious international collaboration to investigate theoretically and experimentally the potential of quantum annealing, IARPA's Quantum Enhanced Optimization effort.

Collaborators

Discussions over the last few months with Prof. Nick Bambos of Stanford University, his student, former NASA Ames civil servant Michael Bloem,(who performed for the CSA work), and Karl Bilimoria heavily influenced this proposal. Prof. Bambos is an internationally recognized expert in areas such as network control, task scheduling, queuing systems and stochastic processing networks. Funding for this project would enable these discussions to bloom into a full collaboration. These relations constitute an invaluable asset for the successful execution of this proposal.

QuAIL is partially supported by NASA's Advanced Exploration System program, which has sponsored, since 2012, our fruitful collaboration with the Planning and Scheduling Group led by Dr. Jeremy Frank.

Our frequent communication with the leading developers of quantum annealing technology, D-Wave Systems, Inc., MIT Lincoln Laboratory, and the Martinis group at Google, will enable the insights gleaned from this work to be incorporated into the next generations of quantum annealing hardware.

---

[6] A Quantum Annealing Approach for Fault Detection and Diagnosis of Graph-Based Systems, A. Perdomo-Ortiz, J. Fluegemann, S. Narasimhan, R. Biswas, V.N. Smelyanskiy, Eur. Phys. J. Spec. Top., 224 (1), 131-148 (2015)
[7] T. F. Ronnow, Z. Wang, J. Job, S. Boixo, S. V.Isakov, D. Wecker, J. M. Martinis, D. A. Lidar, and M. Troyer, Defining and detecting quantum speedup, Science, 345, 420 (2014)
[8] Determination and correction of persistent biases in quantum annealers. A. Perdomo-Ortiz, B. O'Gorman, R. Biswas, and V. N. Smelyanskiy. arXiv: 1503.05679
[9] Quantum Optimization of Fully-Connected Spin Glasses, D. Venturelli, S. Mandrà, S. Knysh, B. O'Gorman, R. Biswas, V.N. Smelyanskiy, PRX (accepted)
[10] Comparative Study of the Performance of Quantum Annealing and Simulated Annealing, H. Nishimori, J. Tsuda, S. Knysh, Phys. Rev. E, 91, 012104. (2014); Open system quantum annealing in mean field models with exponential degeneracy, K. Kechedzhi, V.N. Smelyanskiy, arXiv:1505.05878

A significant objective of this seed proposal is to develop new collaborations. In particular, we wish to expand our interactions with domain experts in NASA Ames's Aeronautics division.

Summary

The results of this study will deepen NASA's understanding of the potential of quantum annealing to aid in the many computational challenges involved in NASA's missions. In particular, this study will broaden our exploration of potential applications to the ATM domain and assess the viability of more efficiently tackling computational challenges in the ATM sector by means of quantum annealing techniques. This initial assessment is meant to guide NASA as to the advisability and content of a larger-scale study.

Proposed budget: $80,000 **Time horizon:** 6 months

Personnel: Collaboration among junior and senior members of the existing QuAIL team and domain experts at NASA. Approximately 1/2 FTE during the 6-month duration of the project.

Deliverable: Report detailing our findings and outlining a general research strategy for exploration of ATM applications of quantum annealing, including recommendations for next steps to be taken at NASA Ames. (See Table 1 for a list of milestones.)

Task/Milestone	**Performance Metric**	**Expected completion**
Map at least two NASA-relevant ATM problems to quadratic binary optimization problems	Number of required qubits. Connectivity measures of the resulting coupling graphs	1.5 months
Compile instances of these problems on the D-Wave 2X and assess resource requirements parameterized families of these problems for different sizes	Largest problem size feasible on current device.	2 months
Design benchmark ensembles of problems suitable for assessment, including scaling analysis	Hardness as a function of size. Ease of problem generation.	3.5 months
Run the problem ensembles on the D-Wave 2X™ system and analyze the data	Scaling of expected time to solution vs. size compared against classical code, variety of different acceptable solutions	5 months
Outlook on different architectures and annealing strategies, hardware changes	Optimal annealing time, optimality of compilation, precision error impact	6 months

Table 1: Breakdown of the proposed effort into milestones, including the suggested performance metrics and completion dates.