UDC 658.1.004

QUANTUM COMPUTING AND ITS APPLICATIONS TO TRANFFIC CONGESTION

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Abstract: With the world slowly advancing towards quantum computing, it is becoming more crucial to understand how it works, and how it could be used to potentially better the world through optimization. This paper will address the history of quantum computing, the logistical make-up of it, how it differs from classical computing, and how it could and is currently being applied to real life applications of traffic regulation through optimization. The particular model of quantum computing being discussed in the application section of this paper uses quantum annealing through the Advantage quantum computer, designed by D-Wave, to explain how Volkswagen is currently optimizing traffic flow with quantum computers.

Early stages:

In 1981, physicist Richard Feynman realized that classical computers had a significant problem: they were slow in simulations of complicated quantum systems. The amount of information required for modeling these systems increased exponentially with the rise of complexity, and there was basically no way for standard computers to cope with this problem. Feynman proposed using quantum computers to solve all such problems in an efficient way, as they work based on the principles of quantum mechanics. In his seminal 1982 paper entitled "Simulating Physics with Computers," he described the way quantum computers would solve problems that their classical counterparts couldn't even contemplate tackling, thus laying the foundation for quantum computing. [1][2].

In the early 1990s the Bernstein–Vazirani algorithm, a quantum algorithm, Ethan Bernstein and Umesh Vaziran, was fundamental in creating the framework for quantum complexity theory, showing that quantum computers can solve certain problems faster than classical ones. Their work paved the way for developing practical quantum algorithms.[3]

Quantum algorithms:

Quantum algorithms are a key part of quantum computing, showing how concepts like superposition and entanglement can solve problems much faster than traditional methods. These algorithms can speed up processes like cryptography, optimization, and database searches, offering huge advantages over classical systems. They're at the heart of quantum computing progress, bringing together physics, math, and computer science to change the way we think about computation. Some examples of important ones are:

Deutsch-Jozsa algorithm is a quantum algorithm that solves specific problems much faster than any classical algorithm, making far fewer queries. It was one of the very first demonstrations of how a quantum computer could be superior to a classical one for some tasks, thanks to quantum parallelism, where the computer can consider many possibilities all at once.[4]

Shor's algorithm is a quantum algorithm that factors large numbers efficiently, something quite challenging for a classical computer. This employs techniques such as the quantum Fourier transform and modular exponentiation to expedite this process. It makes the computation exponentially faster than any classical method, hence having possible implications for cryptography.[5]

Grover's Algorithm is a quantum algorithm that speeds up the search for a solution in an unsorted database. It offers a quadratic improvement over classical search methods, which typically take $O(N)$ time. Grover's algorithm reduces this to $O(\sqrt{N})$, making it much faster for large databases. [6]

Fundamental Make-up:

The fundamental ideas of quantum mechanics, the area of physics that examines how matter and energy behave at subatomic scales, underpin quantum computing. Quantum computers use quantum bits (qubits), which can exist in several states at once, as opposed to classical computers, which process information in bits (either 0 or 1). This feature, called superposition, greatly increases the potential of quantum computers to solve complicated problems by enabling them to compute a large number of possibilities simultaneously [7]. For instance, a qubit can simultaneously represent 0 and 1 in a state of superposition, which is not possible for traditional bits to do [9]. Quantum gates, which change the states of qubits, are used in quantum computing to carry out computations. These gates change the odds of events utilizing operations like flips or rotations [8]. For example, quantum gates are made to take advantage of physical concepts such as the physics Hamiltonian model's description of the minimization of energy states [12]. Quantum algorithms, which use quantum phenomena to solve problems, are based on the conjunction of these gates.

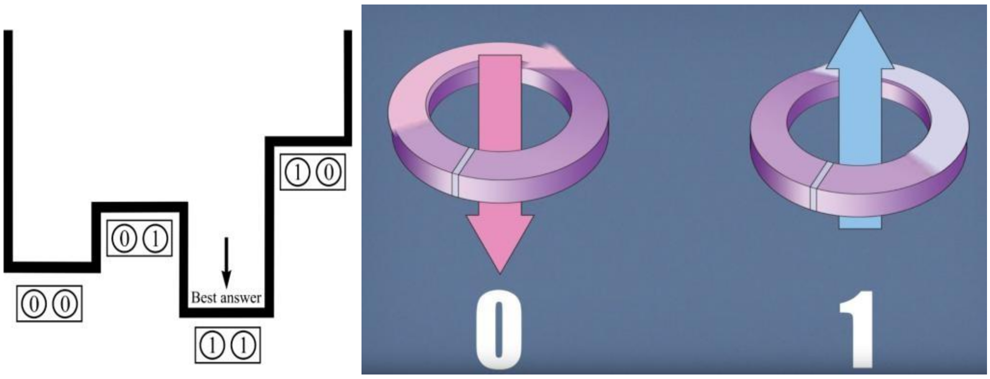

Fig. 1. The two diagrams above were retrieved from [7].

The decision tree diagram in the top figure illustrates how quantum annealing selects the best option from a range of options. It illustrates how qubits are guided to a low-energy state by quantum annealing, which is the ideal solution. Qubits in the two states of 0 and 1 are shown as circular loops with arrows in the second figure. The quantum state of a qubit, which can simultaneously represent 0 or 1, is highlighted in this illustration. These states give quantum computers the ability to investigate several solutions simultaneously, which makes them effective in solving optimization issues [7].

Real-World Application: Across the world, there are a handful of quantum computers, each designed differently. Logistics, material science, and even transportation systems will be significantly impacted by quantum computing's capacity to investigate enormous solution spaces through superposition and entanglement [9]. For the purpose of this paper the Advantage quantum computer designed by D-Wave will be used. D-Wave aims to tackle "real business problems and demonstrating quantum ROI" [8] and has used their quantum computer to solve optimization problems that would take classical computers significantly longer to tackle. The specific model they are currently using for the optimization-related problems is called quantum annealing. Quantum annealing processors "naturally return low-energy solutions" [7] which make them a great tool for optimization problems.

A consistent trend in how the physics of our world operates is that "everything tends to seek a minimum energy state" [7]. As such, the quantum annealing processors are designed to "increase the probability of a qubit ending up in a valley with a lower energy minimum" [7] enabling faster solutions through the application of the Energy Minimization Principle [12]. In development of the annealing model, D-Wave has used this physics principle through the use of a mathematical model referred to as the Hamiltonian equation which incorporates the tendency of a system wanting to minimize its energy [12]. D-Wave has provided an image explaining the process of annealing in which an external magnetic field is enforced on a qubit to manipulate its probability, causing it to end in a lower energy state:

Traffic congestion is one of the issues experienced by most people on a daily basis. As such, Volkswagen set out to use quantum annealing to improve service speed and reliability for a bus operator CARRIS [10].

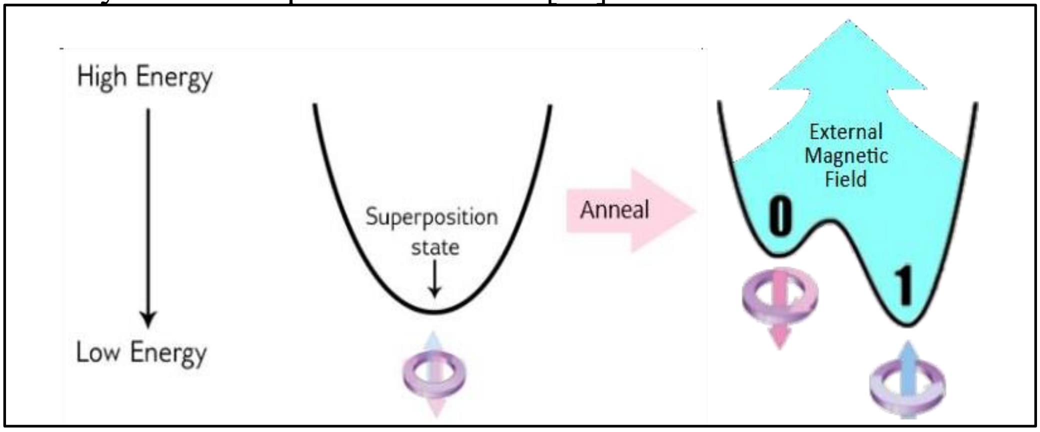

Fig. 2. The two diagrams above were retrieved from [7].

In this application, the principle of quantum annealing was used to find the best answers to issues by guiding qubits gradually toward a low-energy state incorporating the fundamental thermodynamic premise that physical systems have an innate drive to decrease their energy. Their system incorporated two components: "passenger number prediction and route optimization" [10] where Volkswagen developed an algorithm to "calculate the fastest route for each individual bus in the fleet [that would] optimize it almost on a real-time basis"[10] allowing each bus driver to follow an individually calculated route that would provide the more efficient method of travel to the intended destination to avoid "traffic jams before they even arise"[10]. After the design and implementation of this project, Volkswagen was able to develop a "hybrid algorithm that relies on both classical and quantum approaches to problem solving" [11].

Conclusion:

Quantum computing is changing the industry approach to optimization that offers a higher-level efficiency, and faster processing functions that classical computers cannot match. Quantum computing is expanding into more areas of influence and practical application using complex problem solving to drive innovation. Many companies are starting to integrate quantum computing into their operations to approach real-world problems through new and innovative approaches. Similar to Volkswagen's approach to ending traffic congestion, many companies are currently trying to explore how quantum computing can be used alongside classical computing to use the strengths of both through hybridization to solve the issues being presented.

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«Автомобільний транспорт та інфраструктура»

AutoTransport and Infrastructure

17-19 квітня 2025 року
м. Київ

УДК 631.17+62-52-631.3

Рекомендовано до друку рішенням вченої ради механіко-технологічного факультету Національного університету біоресурсів і природокористування України від 20 травня 2025 р., протокол №. 12

Збірник тез доповідей VIII Міжнародної науково-практичної конференції «Автомобільний транспорт та інфраструктура» (17–19 квітня 2025 року). Національний університет біоресурсів і природокористування України. Київ. 2025. 242 с.

ISBN 978-617-8530-21-1

В збірнику представлені тези доповідей науково-педагогічних працівників, наукових співробітників, докторантів і аспірантів, студентів, фахівців транспортної галузі, учасників VIII Міжнародної науково-практичної конференції «Автомобільний транспорт та інфраструктура», в яких розглядаються нинішній стан та шляхи розвитку автотраспортної галузі.

ISBN 978-617-8530-21-1

ОРГАНІЗАЦІЙНИЙ КОМІТЕТ:

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Савченко Л.А., завідувачка кафедри транспортних технологій та засобів у АПК НУБіП України;
Софі Лю, професор Університету Орала Робертса (США);
Степанов О.В. заступник декана з наукової роботи механіко-технологічного факультету НУБіП України.