Impact of Quantum Computing on sectors in society based on its application to real-world use case problems

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ABSTRACT

Quantum computing (QC) was first introduced in the 1980s by Paul Benioff. Since then, QC has been gaining popularity in the scientific and business community. Private and public investments of companies have been estimated at over 33 billion dollars for the development of QC. Why are people investing so much in QC and quantum computers? We already have normal computers that can perform almost all the tasks in our daily lives. Researchers believe that QC can overcome the current computational limitations of computing both in speed and efficiency. This means that quantum computers might be able to find solutions faster, to problems that are considered of NP complexity and have been identified to have real-world use case applications. However, this does not mean that quantum computers will replace normal computers. In this paper, we will first introduce the basics of QC to the reader. Then we will examine some of the applications of QC to computational problems. We will then discuss the impact of QC on real-world use case problems, as well as mention the current limitations and drawbacks of QC and quantum computers.

KEYWORDS

Quantum computing, quantum computers, application, impact, limitations

1. INTRODUCTION

Quantum computing has existed for almost four decades now [6] and has been a field of research for many scientists [27]. Governments and companies have already invested billions into QC with the belief that QC is the future of computing [28]. However, quantum computing is still in the early phases of its development. The current phase of quantum computers can be compared to the time when classical computers were still as big as rooms and could do very little while consuming a lot of energy and being hard to maintain [8]. There are already some articles that provide explanations of what quantum computing is, how it works, or how to create quantum computers [4, 11, 29]. However, none of these articles includes a simple summarized explanation, understandable for a reader that does not have any prior knowledge of the topic of QC. Furthermore, many of these articles are already outdated, as quantum computing is an ever-evolving study, and some of the information is proved wrong or new information is found, e.g., new materials to develop quantum computers [1].

After finding out what quantum computing is, we continue to the second part. Where can it be applied? There have been many announcements that the moment quantum supremacy (QS) is achieved, most NP problems will be solved. Quantum supremacy is a term used by many scientists to describe the achievement of creating quantum computers that cannot be simulated with normal computers or supercomputers. Quantum computers will have exponentially more computational power compared with the computers that we have currently. NP problems are part of the computational complexity theory. In this theory, we have three types of NP problems. P problems that we know how to solve and have the computational power to solve. NP-Hard problems that we do not know if an answer to exists and do not possess the computational power to solve. NP-Complete problems which we know how to solve in theory but do not possess the computational power to verify the answer. This means that complex NP-Complete problems will take hundreds of years to be solved with the current computers that we have. Some examples of problems that are considered in the NP complexity class are the "Traveling Salesman Problem" (TSP) [20, 35], "Knapsack Problem" [9, 31] and "Vehicle Routing Problem" (VRP) [3]. Achieving QS means that quantum computers will be able to solve highly complex NP problems faster compared to classical computers [18]. This means that QC will have an impact on sectors in which the NP problems have identified use case applications. The use cases and impact of QC on them can be seen in the next examples. TSP can be applied in the transportation sector, knowing the shortest path between distances will make deliveries faster, or optimize bus routes and save money [35, 38]. The Knapsack problem can be applied to optimize the distribution of cargo in vehicles, which would reduce the number of trips needed [9]. Of course, TSP and Knapsack problem can be applied to other sectors as the examples above were just one of many [7].

For this research, a literature review will be the main source of information. There are many articles and books which contain the newest information and give the best insight on the topic. The expected contribution is for the readers to get a better grasp of QC.

2. PROBLEM STATEMENT

As mentioned in the introduction, there are a lot of articles in the field of quantum computing with more being published each day. Most of the articles focus on four things: introducing readers to QC, showing how NP problems are solved with quantum

TScIT 37, July 8, 2022, Enschede, The Netherlands

computers, showing where QC can have a potential impact and analyzing that impact on a real-world problem, and providing the limitations that exist in QC. However, most of the articles do not provide a simplified summarized answer to all four problems in one article.

2.1 Research Question

The above-mentioned problem statement leads to the following research question:

What impact will quantum computing have on sectors of society based on its real-world use case application?

This research question can be answered with the following sub-questions:

1. What is QC and what are quantum computers?
2. What are the applications of QC and quantum computers?
3. Where can QC and quantum computers have an impact?
4. What are the current limits of QC and quantum computers?

3. RELATED WORK

The field of quantum computing has been around since the 1980s and is regarded as a very important topic of research [6, 27]. Because of that, various researchers have and continue to do extensive research and experiments to further help advance the field [27].

The articles from Bernhard and Hughes [8, 19] provide a good basis on which one can get a general knowledge of quantum computing. However, both articles from Bernhard and Hughes require a good understanding of mathematics and physics.

Solving NP problems with QC is a topic that has been researched by many scientists [20, 9, 31]. Jain's solution to the TSP [20] problem and Coffey's solution to the Knapsack problem [9] are one of many different solutions to problems that are considered in the complexity class of NP.

Identifying the commercial application of QC and its impact has received extensive research. Bova [7] and Navaneeth [22] analyzed some of the potential impacts of QC based on its commercial applications. Bayerstadler [5] analyzed the impact of QC on different real-world use case applications. Elsayed [14] and Fellous-Asiani [15] have identified different challenges and limitations to QC and quantum computers.

There have been many articles related to the research question, however, none provide the answer in a way that could be understood by the layman.

4. METHODOLOGY

In this section, we explain what steps will be used to answer the research question.

First, literature will be gathered mainly focusing on scientific articles and books. To find appropriate literature, the main sites that were used were ACM Digital, IEEE Explorer, Scopus and Web of Science. The appropriate literature was then analyzed and the parts that were most relevant to the research question and sub-questions were used.

4.1 What is QC and what are Quantum Computers?

This question is important and relevant for the paper because the next questions cannot be answered without first knowing the basics of QC and quantum computers. To answer this question the above-mentioned sites were used and the keywords and search queries that were issued were "Quantum computing", "Quantum computers", "Quantum superposition, "Quantum Entanglement", "Quantum annealing" and "Gate-based QC". When issuing these keywords and queries, we searched within "Article title", "Abstract", and "Keywords".

4.2 What is the Application of QC and Quantum Computers and where will QC have an impact?

Together, these two questions form the core of the paper. We consider them as the core because the questions will show to what type of problems QC and quantum computers can be applied. After which we can analyze this application and connect it to real-world use case problems. Then we can see in which areas QC can have an impact and understand, how it impacts real-world use cases. To answer these questions the keywords and search queries that were used are "Application AND QC OR Quantum computers", "Impact AND QC OR Quantum computers", "TSP AND QC OR Quantum computers", "Knapsack problem AND QC OR Quantum computers", "VRP AND QC OR Quantum computers", "Energy Optimization AND QC". The queries were searched within "Article title", "Abstract", and "Keywords" and the filter was set to most relevant. The resulted articles were filtered to be no older than 3 years, or in other words, the articles had to be published after 2019.

4.3 What are the current limits of QC and Quantum Computers?

After we know the applications of QC and how it can impact different sectors, it is important to discuss its current limits. The limits are important so that people with interest can know how advanced the technology is. To answer this questions, the keywords and search queries that were used were "Limits AND QC", "Limits AND Quantum computers", "Current state of Quantum computers", and "Limitations AND (quantum annealing) OR (gate-based quantum computing) AND devices". The queries were searched within "Article title", "Abstract", and "Keywords" and the filter was set to most relevant. The resulted articles were again filtered to be no older than 3 years.

5. WHAT IS QUANTUM COMPUTING AND WHAT ARE QUANTUM COMPUTERS

QC is a new branch of computing that exploits principles in quantum mechanics for computational purposes. To properly grasp how QC works and how quantum computers function, we will explain six fundamental terms: quantum superposition, quantum bit, quantum entanglement, quantum parallelism, gate-based quantum computing and quantum annealing.

Quantum superposition [8, 19, 23] is a phenomenon that occurs in quantum systems. A system can be described to be in a state. A state is related to a quantized value. For example, a card can be either in-state face-up or in-state face-down. A quantum state can be in a superposition state where the superposition state is a combination of all possible states at the same time, but the moment the superposition state is measured, it becomes one of the definitive states. The famous experiment Schrödinger's cat [33] created by Erwin Schrödinger will provide a good example of a quantum superposition state. Schrödinger's Cat is a thought experiment where a cat is placed in a box with an atom that emits deadly radiation when it decays. Scientists cannot predict with certainty and accuracy when atom decay will happen because it is a spontaneous process. Because of the spontaneous decay, we cannot be certain if the cat is dead or alive in the box until we open the box and observe the state of the cat. If the cat is dead when observed, we are in state 0. This results in three possible states 0 if dead, 1 if alive, and a superposition state, which is any combination of the 0 and 1 states.

Quantum bits or Qubits, in short [8, 19, 23], are the smallest unit of information in quantum computers and have two measurable states, 0 and 1, similar to classical bits. However, qubits can also be in a superposition state, which is a combination of the 0 and 1 states. The moment the qubit is measured, it can be either in state 0 or in state 1. Figure 1 provides a good representation.

Figure 1 Source: [39]

A qubit can be represented by a Bloch sphere, where the top and bottom of the sphere represent the measurable states $|0\rangle$ up and $|1\rangle$ down. An arrow in the Bloch sphere can point to any direction in the sphere which represents the current state. Figure 2 demonstrates an example of a Bloch sphere with a qubit in four different states, if the arrow is not pointing towards the top or bottom the qubit is in a superposition state and has a 50% chance to jump to either of the two measurable states.

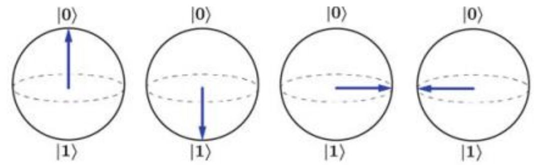

Figure 2 Source: [19]

To express the states of a qubit Paul Dirac [13] proposed names for two specific vectors: a ket, which is a column vector and is denoted by $|v\rangle$ and a bra, which is a row vector and is denoted by $\langle w|$. A qubit has the form of $a|0\rangle + b|1\rangle$ where "a" and "b" are called probability amplitudes and $|0\rangle$ is spin up, while $|1\rangle$ is spin down. "a" and "b" can be any number, but are generally complex numbers. One can imagine probability amplitudes as dropping two stones into water generating waves. The waves can either be in phase, increasing the amplitude of the wave by building each other (constructive interference) or out of phase, decreasing the amplitude of the wave by cancelling each other (destructive interference) as shown in Fig 3.

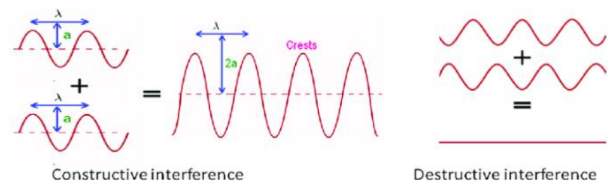

Figure 3 Source: [40]

Probability amplitudes can be used to represent all possible superposition states, but they also give us the probability of finding a particle in a specific state when being measured. When we measure a particle, the probability of it jumping to state $|0\rangle$ is $|a|^2$, and the probability of the particle jumping to state $|1\rangle$ is $|b|^2$.

Quantum entanglement [8, 19, 23] is a physical phenomenon that occurs when multiple electrons or qubits are correlated with each other. Using the entanglement property, the spin of an electron can be correlated with the spin of another electron. This means that before measuring either of the two entangled electrons, they can be in a superposition state of both spin-up and spin-down. The moment the spin of either of the two entangled electrons is measured, the information is communicated to the other electron, and that electron assumes an opposite spin direction to that of the measured electron. Figure 4 shows entangled electrons.

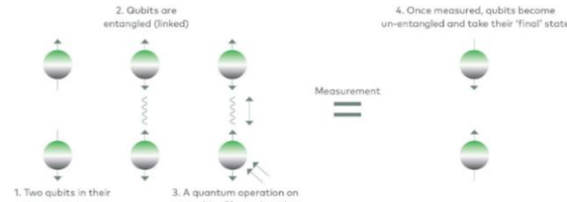

Figure 4 Source: [39]

To provide an example of this phenomenon, we will use two fair coins. Classically there are four measurement outcomes if you flip the coins: TT, TH, HH, and HT, each with a 25% probability of happening. Now, if we quantumly entangle these fair coins, it is possible to create a state $(1/\sqrt{2})(|HH\rangle + |TT\rangle)$ which means that if one coin lands on one side, the other will land on the same side as the first coin. So there are now two measurements: either we have HH or we have TT with 50% probability. There are many other types of entanglement, but this was the most famous example called the Bell state [8, 19].

There are different physical implementations of qubits, but we will focus on creating a qubit by manipulating the spin state of an electron. To create a qubit, we need a property with two measurable states, and electrons have a two-state property called spin. It is considered a two-state property because electron spin can be up or down but it can also be a combination of the two as shown in Fig 5. With the help of magnetic and electrical fields [19], there are ways to manipulate the spin state of an electron to create superposition, entanglement and other properties.

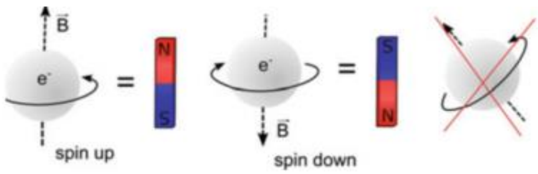

Figure 5 Source: [19]

Quantum parallelism [23] is a fundamental feature of quantum algorithms. Classical parallelism is when multiple circuits are each built to compute a function f(x) and are executed simultaneously. For example, if we want to find x = 0 and x = 1 two classical computations are needed that run parallel to each other. Unlike classical parallelism, in quantum parallelism, only one circuit is built and used to calculate a function f(x) for many different values of x simultaneously. This means that quantum parallelism enables all possible values of x to be evaluated simultaneously. Quantum parallelism is possible because quantum computers exploit features like superposition and entanglement. However, it is important to note that there are limitations to quantum parallelism, which will be discussed in a different section.

Quantum algorithms are programmed with the help of gate-based quantum computing. Gate-based quantum computing works by creating circuits with qubits, which represent multiple states at the same time. When quantum gates (NOT, AND, OR, CNOT and others) are used on qubits, each operation is applied to all states simultaneously due to quantum parallelism implying an exponential speedup in computing capability. The only problem is that it is not possible to directly read the results of such quantum parallelism. Only cases where the same end state can be reached by more than one different path can be used because the amplitudes connected to each state can be summed up to determine the amplitude of the end state (Young's double-slit experiment). Some of the manufacturers of quantum computers that use gate-based computing are IBM, Quantum Brilliance and Honeywell [30].

Quantum annealing is an alternative to gate-based quantum computing. Quantum annealing is an optimization process that uses quantum fluctuations to find the global minimum of a given function over a given set of candidate solutions. To find this minimum, a set of qubits are prepared and, when measured, the qubits would represent a single candidate solution to the optimization problem. For each possible solution, a potential energy level is defined, where lower energy levels represent better solutions. Originally, the system has enough kinetic energy to reach each viable configuration. But a cooling process is simulated and as time passes, temperature and consequently kinetic energy are reduced. The drop in energy results in the availability of low-energy configurations that can be represented as values in a matrix. These values in the matrix can be checked to see if good solutions have been achieved. To control the energy levels and simulate a cooling process, a Hamiltonian is used. A Hamiltonian represents the energy levels of a system. The final Hamiltonian is equal to the sum of the initial Hamiltonian and the problem Hamiltonian. The lowest energy state for the initial Hamiltonian is when all qubits are in a superposition state. The lowest energy state for the problem Hamiltonian is the answer to the problem. We start at the initial Hamiltonian and introduce the problem Hamiltonian. As the cooling process goes on, the influence of the initial Hamiltonian is reduced until an answer to the problem is found. Fig 6 provides an example of four sets of qubits with different energy levels, each representing a candidate solution when measured. D-Wave, Fujitsu and NEC are some of the manufacturers that offer devices that use quantum annealing [30].

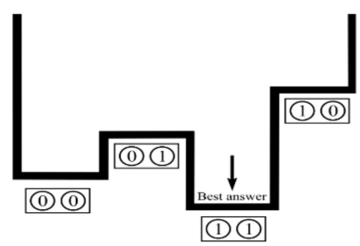

Figure 6 Source: [41]

6. APPLICATIONS OF QC AND QUANTUM COMPUTERS

QC offers computational power that is far greater compared to the one that classical computing provides. However, that does not mean that we can apply QC to everyday use such as browsing the internet or sending emails. There are specific classes of mathematical problems that expose the limits of classical computing. QC holds the ability to overcome these computational limitations that classical computers have stumbled upon. Many of these mathematical problems are classified as NP-hard problems in combinatorial optimization and include algebraic, optimization (Knapsack problems), graph (TSP, Graph colouring problems) and combinatorial problems. These problems can be formulated as Quadratic unconstrained binary optimization (QUBO) problems and have a large number of applications in the real world, such as load optimization, energy optimization, transportation modelling, banking and finance and many more. With the help of quantum annealing and gate-based quantum computing, many solutions to these problems have been developed. In the following paragraphs, we will dive deeper into the solutions to these mathematical problems and their optimization applications to real-world use cases.

NP is a complexity class in computational complexity theory. For some of the problems in the NP class when a solution is found, it can be checked on a classical computer quickly to verify the answer. However, the time needed to find a solution for NP problems grows exponentially with the complexity of the problem. In other words, if there are more variables, the problem is harder to solve. Some NP problems are TSP, Knapsack problem, VRP, Unit commitment (UC) problem and others. Classical computers struggle to find optimal solutions to NP problems because they have to evaluate all possible variables for a function one at a time. And even if algorithms that reduce the search space are used, as the complexity of the NP problem grows, the time needed to find a solution becomes exponentially long. Quantum computers, on the other hand, in theory, might be able to solve these NP problems exponentially faster due to quantum parallelism, entanglement, and superposition. To date, there is no specific procedure to follow, but various cases have been demonstrated which exploit the computational speedup connected to quantum parallelism. However, all these methods depend on amplitude manipulation to affect the desired results when the amplitudes are combined. The most famous examples are Shor's algorithm for factorizing large integers [25] and Grover's algorithm for unstructured search [21]. The former algorithm has a time complexity of $O(\log^2 n)$ compared to the time complexity of $O(\sqrt{n})$ from a classical algorithm, or in simpler terms, Shor's algorithm provides an exponential speedup. The latter algorithm provides a time complexity of $O(\sqrt{n})$ compared to O(n) from a classical algorithm, which is a quadratic speedup.

6.1 The Knapsack Problem and a QC Solution to its Real-World Use Case Application

The NP-hard Knapsack problem is one of the combinatorial problems that can be used for the optimization of real-world problems. The main aim of the Knapsack problem is to pack an optimal collection of items such that the weight is less or equal to a given limit while the value of the items is maximized. One of the main applications of the Knapsack problem to real-world problems is supply chain management, such as cargo optimization, truck loading, lot sizing, aeroplane loading and demand capacity match. Coffey et al. [9] reformulated the Knapsack problem into a QUBO problem so that they could apply it to cargo loading. Their formulation was as follows: maximize the transported load, with a constraint that the load volume is equal to or lower than the max volume of the knapsack, where the weight and volume of each item are given. Then Coffey et al. developed a quantum annealing solution [9]. In their solution, a Hamiltonian H that solves the problem is divided into two: $H = H_A - H_B$ where H_A puts a restriction that the maximum volume is not exceeded and H_B which solves the weight optimization problem. The different configurations of objects that are carried determine the value of H. The configuration of objects with the lowest value is the optimal solution that maximizes the transported load and fulfils the restrictions.

The Knapsack problem can be formulated as a QUBO problem to have real-world use case application and then solved on a quantum annealing system like the D-Wave [31]. Rafael Sotelo et al. [31] proposed such a QUBO formulation and solution. They expanded the above-mentioned knapsack solution of Coffey's with one more restriction: a maximum load capacity. This resulted in a Hamiltonian that had three parts: $H = H_A + H_C - H_B$, where $H_A$and H_B represent the volume restriction and total weight, while H_C represent the weight restriction. The solution is encoded in a state vector where the lowest value of H is the one that maximizes the cargo subject to the restrictions that neither the weight nor the volume is exceeded.

6.2 The TSP Problem and a QC Solution to the Real-World Use Case Application of VRP

The NP-hard TSP is an optimization problem in graph theory that has many real-world use case applications. In the TSP, we are given a list of cities and the distance between them and we are asked for the shortest path that visits each city exactly once and returns to the starting city. TSP has many real-world use case applications in transportation and logistics, such as vehicle routing, traffic flow optimization, fleet management, delivery of items and more. Saul Gonzalez-Bermejo et al. [16] have proposed one solution to the TSP problem. In their solution, they divide the Hamiltonian H into three parts: $H = H_c + H_m + H_t$ where each part represents three constraints: the salesman must leave each city once, each city must be reached once and if the salesman leaves a city, he cannot return to it. The shortest path that is found determines the value of H. The lowest value of H is the optimal solution that fulfils the restriction.

The above-mentioned solution to the TSP can be used for the solution of the VRP. The VRP is a generalized TSP and asks for the optimal set of routes for a fleet of vehicles to travel to deliver items to a given set of customers. A solution to this problem was proposed by Akshay Ajagekar et al. [3]. In their solution, the Hamiltonian H is divided into two parts: $minH = H_{obj} + AH_c$ where H_{obj} represents the total weight of the cost of all other sections of the route information included in the route, H_c represents the total sum of all travel costs of vehicles from the depot through the cities and back to the depot and A is the penalty weight. The constraints put on the problem are: each customer must be visited and serviced exactly once by one vehicle and the second constraint enforces each vehicle to leave for another customer or the depot in the next step of its route. The lowest value of H is the optimal solution to the VRP.

6.3 Application of QC to Energy Optimization and a QC Solution to UC

A fundamental problem in the electrical power industry is matching the generated energy from power systems to the energy demand at a minimum cost. A solution to this problem is necessary because of two factors [2]. The first factor is that it is difficult to store generated energy to the scale needed to supply normal daily consumption, especially if it is green energy from wind or solar farms. The second factor is that energy-generating units require time to start up. This means that the decision on which energy generating units need to be used must be made in advance and fast to satisfy the energy demand for that specific period. The NP-hard UC problem is an optimization problem in the electrical power industry developed to represent the problems with the operation of power systems [2]. UC problem aims to minimize the total cost of power generation in a specific period by creating sufficient scheduling of the generators. The solutions must adhere to specific constraints: system power balance, spinning reserves and generation power limits of each unit. Figure 7 represents a combination of different units matched to different power demands.

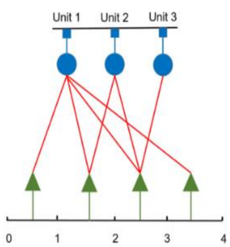

Figure 7 Source: [2]

The UC problem is difficult to solve because it is a combinatorial problem that has a lot of variables and a large set of feasible solutions. Akshay Ajagekar et al. [2] proposed a solution to this problem. In their solution, they reformulate the problem to be in a QUBO model, so that it can be mapped on a D-Wave system. The solution to the reformulated problem $H = F + P + O - L$ finds the minimal value of power generation H, where F represents the fuel cost of all committed units, P represents the amount of generated power to satisfy a given unit, O represents if a unit is online or offline and L represent the required load.

7. IMPACT OF QC AND QUANTUM COMPUTERS

QC, as seen in the previous sections, is a new field in computing that has many applications. Consultancy companies identified the large number of distribution use cases that QC has. These use cases can be seen in Figure 8.

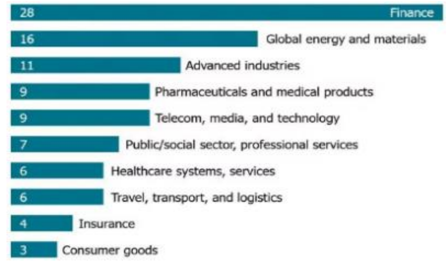

Figure 8 Source: [42]

Because of the large use-case application of QC, we can analyze the domains in which QC can have an impact. Our focus on the impact of QC will be divided into two categories. The first will be on the industry. Because QC can impact complex optimization, simulation and machine learning challenges, we can see how QC will impact the industry. The second will be on society and more concretely on problems that have been identified in society such as affordable and clean energy.

7.1 Impact of QC on the Business Industry

Quantum Application and Technology Consortium (QUTAC) is a German organization that was formed to advance the German quantum computing economic system [5]. QUTAC has ten forming members, the most famous of which are BWM, Volkswagen, Bosch and Siemens. QUTAC aims to advance QC to a large-scale industrial application level and to identify commercially attractive solutions to high-impact business problems. QUTAC focused on four areas in the business industry: material science, engineering and design, production and logistics, and post-quantum security. In these four areas, QUTAC determined that QC can have the highest impact compared to other areas. However, the precise and proven business impact of QC cannot be provided, as this business impact depends on both technical (number of qubits, accuracy of solutions) and business details (values associated with model types) [5]. Even though the impact of QC on the business industry cannot be analyzed currently, the impact of QC on business applications can be. Optimization problems such as TSP, Knapsack and their variations exist in the production and logistics domain across all sectors in the business industries and QC provides quantum solutions to these optimization problems. The quantum solutions might prove to be faster and more accurate in real-time compared to classical solutions, which is why many companies are adopting QC solutions in their business applications. As a result of this adoption of QC solutions, we can analyze the impact of QC on business applications.

As mentioned in the previous paragraph, the TSP and Knapsack problem have many use-cases in the logistics and optimization domain. Thanks to this large application, many companies have already identified relevant use-case scenarios for their business problems. The companies have invested and made substantial research and progress to find optimal quantum solutions to these business problems. Some of these business problems include the Multi-car paint shop problem (MCPS), VRP, robot path optimization, portfolio optimization, route and traffic optimization, cargo optimization, warehouse optimization and many more. Volkswagen is one of the companies that has identified the use cases of the MCPS in their paint shops [37] and traffic flow optimization [38] in their business applications and has invested in QC solutions. In the following paragraphs, we will discuss how Volkswagen found QC solutions to these problems and what the impact on the business application was.

7.1.1 Volkswagen's Quantum Solution to their Paint Shop Problem

Volkswagen, together with a research team from D-Wave Systems, partnered [37] to find a solution to the MCPS problem. An essential step of car manufacturing in Volkswagen is to paint the car body before assembling it. This can be viewed as a sequence of car bodies entering the shop, being painted and leaving the shop. Each car body is painted in two independent steps: the first layer is called filler and is the initial coat of paint, and the final layer is the base coat painted on top of the filler. The base coat can be in many colours, while the filler has two options: white for light base colours and black for dark base colours. Volkswagen and the research team focused on filler optimization and defined the problem as follows: Minimize the number of switches needed between white and black filler to paint a sequence of car bodies. Then a quantum solution was created and implemented on a D-wave computer and data was collected from Volkswagen's paint shop. The data was collected for a period of one year with multiple independent car sequences. Each car sequence represented one week of production, with a total of 104,334 cars used. All the data was stitched into one continuous block and a variety of input sizes was generated without permutating the car order for the experiment. The generated problems were of two instance types: small-scale (10-100 car bodies) and industrial (300-3000). Three types of solvers were used on the generated problems: Classical (Random, Black-First, Tabu search), Quantum (D-Wave 2000Q, D-Wave Advantage) and Hybrid Solver Service (HSS) (D-Wave Hybrid Solver). From the measured results, the Classical solvers were able to solve instances of the problem up to 300 cars, after which the time necessary to solve was above 24 hours and was terminated. The hybrid solver performed the best, giving the best solutions and taking the least amount of time. The quantum solvers provided the same solution that the hybrid solver provided and could solve instances up to 3000. However, after instances with 100 cars, the solutions of the quantum solvers deteriorated and were of no usable quality, mainly because there weren't enough sufficient samples.

7.1.2 Volkswagen QC Solution to the Traffic Flow Optimization Problem

Cities are growing in traffic congestion around the world. During sports events, conferences, and festivals, the transportation network suffers significant disruptions. This traffic flow optimization (TFO) problem can be considered a variation of the VRP and can be formulated as a QUBO problem so that it can be solved on a D-Wave Systems computer. Volkswagen partnered with the city of Lisbon during the Web Summit of 2019 [38] to test a QC-based traffic optimization. The traffic optimization problem has been addressed as follows: Design a customized bus route to avoid traffic congestion during big events and build a real-time quantum computer application to manage the traffic system. The application was named "Quantum Shuttle" and was live for four days during the Summit. Nine buses were controlled by people who followed turn-by-turn navigation instructions of a custom Android app. The app received information from a D-Wave QPU (Quantum processing unit) that was performing route optimization tasks. Four specific bus lines were created with specific stops from different points in the city to the Summit and back. No specific route was created between each stop, and they were navigated solely on quantum navigation services. The algorithm to solve the optimization tasks was first embedded on a D-Wave 2000Q solver. But was found insufficient for a TFO problem with more than 10 buses with 5 roads each. Because the solutions obtained by the QPU degraded when the problem size increased, which meant that it could not be scaled accordingly. After deciding that a D-Wave 2000Q solver was insufficient, the problem was embedded into an HSS. The HSS could handle hundreds of buses with tens of roads without any deterioration in the solutions. After performing the tests for four days, the results were: 185 trips, 167 of which were valid (the bus drivers cancelled the trip). 1275 optimization problems were solved with an average time of 4.69s. 728 of those optimization problems involved more than one route per vehicle, meaning that the majority of every route was different from every other vehicle in the fleet. This means that with the help of the Quantum Web System, the buses were able to both avoid existing congestion and not create new congestion.

7.2 Impact of QC on Problems in Society

In 2015, the United Nations Member States (UN) adopted the 2030 Agenda for Sustainable development [32]. At the heart of the Agenda lay 17 Sustainable Development Goals (SDG) which call for urgent action. Zapata computing one of the leading companies that build and offer quantum software applications identified 5 SDGs on which QC can have an impact [36]. One of these was SDG 7: Affordable and Clean Energy. Because there is a rising demand for energy while also a need for environmental protection, one of the main goals of SDG 7 is to create energy optimization. Energy optimization can be achieved by making energy services cheaper and more reliable, as well as improving the efficiency of the energy services. An essential problem for energy optimization is the facility location and allocation problem. One example of this optimization is determining the optimal locations to place wind farms to maximize the energy capture. Another example is determining the optimal location of energy-generating facilities to minimize the costs of energy transportation to satisfy demand costs.

A research team developed a quantum algorithm to find a solution to the facility-location allocation problem. Akshay Ajagekar et al. [2] addressed this problem in a power-grid optimization situation and it was formulated as follows: Minimize the cost of interplant transportation of one energy unit by optimally assigning x powerplants to x region [2]. Then a quantum solution was developed and implemented on a quantum computer D-Wave 2000Q. A classical computer was also used with a Gurobi algorithm implemented on an Intel Core i7-6700 CPU to compare the validity and accuracy of the solutions as well as benchmark the performance of the quantum solution. Then problem instances of sizes between 3 to 20 facilities and locations were created and solved on both the classical computer and the quantum computer. The classical computer was able to solve instances of sizes up to 14, after which it was stopped due to a time limit of 12h. The quantum solver was able to solve all instances and performed significantly faster on smaller instances compared to the classical solver, while also providing the same solutions as the classical solver. It is also important to note, as mentioned by the researchers, that if a hybrid solver was used, the time and quality of each solution would be better.

8 CURRENT LIMITATIONS OF QC AND QUANTUM COMPUTERS

We have now discussed the applications and impact of QC on different problems. We also analyzed the performance of QC against classical computing on those problems. However, we are now going to talk about the current challenges and limitations of QC and quantum computers.

Quantum computers, compared to the best supercomputers, require 100 times less energy consumption while outperforming them on specific problems [14]. However, one of the drawbacks is that to build a quantum computer, one needs approximately 15 million dollars [14]. This is because QPU requires specific cooling systems that keep the temperature at 0 kelvins and pressure that is 10 billion times lower than the atmospheric [14].

The biggest limitation that currently exists for quantum computers is that to build a more powerful quantum computer, one needs to increase the number of qubits. However, with the increase of qubits, the noise or decoherence is also increased [24]. Noise or decoherence, in this case, means that there will be an uncontrolled interaction between the qubits in the system and the environment. This uncontrolled interaction with the environment would lead to the loss of the quantum states and quantum properties of the qubits. This limitation opens a few drawbacks in QC. First, noise-correction algorithms need to be used [24]. Noise-correction algorithms use some of the qubits to correct faults that occur in other qubits. This lowers the maximum performance of the QPU, as not all qubits are used to calculate problems. Second, a scalability issue occurs because of the limited quantum hardware. This means that complex problems with many variables cannot be solved as the search space becomes too big [2].

9. CONCLUSIONS

In this paper, we provide an overview of the impact of QC on real-world use case problems that relate to sectors in society. Although we cannot answer the main research question fully due to limitations in the literature and the technology as a whole, we can answer the sub-question and provide a partial answer.

9.1 What is QC and What are Quantum Computers?

We have explained the main properties of QC and quantum computers. We can conclude that QC is a new branch of computing and that quantum computers are devices that are fundamentally different compared to classical computers.

9.2 What are the Applications of QC and Quantum Computers and Where can QC and Quantum Computers Have an Impact?

We show that currently, the main applications of QC and quantum computers are for computational problems that are of NP complexity. We do this by discussing problems like the TSP and Knapsack and how QC and quantum computers solve them. We relate the applications of QC and quantum computers to real-world problems and show the impact of QC and quantum computers on them. We show that Volkswagen used quantum computers to solve paint shop and traffic flow optimization problems and that the quantum solvers performed better compared to classical solvers. We also show that QC can be used to solve SDG, as seen from the energy optimization problem, where again quantum solvers performed better compared to classical solvers. From this, we conclude that QC and quantum computers have an impact on sectors in society in which computational problems exist.

9.3 What are The Current Limits of QC and Quantum Computers?

Currently, the main limits of QC and quantum computers are. The costs needed to build and maintain quantum computers. The uncontrollable interaction of the qubits. Decoherence/Noise in the system created by faulty qubits. Loss of computational power and limited applications, as well as the need to use hybrid solvers. Limited research in the industry on the impact of QC because of the small numbers of existing quantum computers and their expensive costs.

10. FUTURE WORK

As seen throughout the research, there is a limited amount of available research on the impact of QC on society based on its use case applications. For future work on the subject, there should be more research on the impact of QC and quantum computers in society and a more in-depth analysis of the impact of QC and quantum computers on already existing use cases. One suggestion is to research the impact of QC on truck drivers that use quantum navigation services similarly to Volkswagen's Lisbon experiment. Another suggestion is to develop a model with which one can accurately measure the impact of QC. Future research could also involve the analysis of the carbon footprint of companies that use quantum computers against companies that use supercomputers. This could be done when quantum computers as technology become more stable and are used by more companies.

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