The D-Wave quantum computer – advantages and disadvantages of moving away from the circuit model

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The paper is based on a thesis with the same title. The purpose of this thesis is to analyse D-Wave devices using quantum effects. The research focuses on demonstrating the advantages and disadvantages of a company moving away from the circuit model in its computers. The subject of the research is the used adiabatic model of quantum computing based on the mechanism of quantum annealing. The research is based on publicly available, comprehensive documentation of D-Wave Systems. On the basis of scientific papers, conferences and information contained in websites, controversies, disadvantages and advantages of the solutions adopted have been described.

Keywords: D-Wave, quantum computer, quantum annealing

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1. Introduction

Over the years, the fate of the world has changed as a result of inventions that were innovative at the time. The last such device is considered to be a computer. We are currently unable to imagine a life without access to these technologically advanced devices. According to the Central Statistical Office in Poland: "In 2019, at least one computer in the home was owned by 83.1% of households with at least one person aged 16–74." [10] The situation is similar in most developed countries, in the case of Europe it takes a result of 84%. [4] Thus, we can observe a global level of informatization of society. Over many years there has been an intensive development of computer technology which seems to be waning. Many scientists and researchers consider the quantum computer as the next milestone. Quantum devices are said to revolutionize the market and to have a real impact on many sectors of the economy. An intensive race has started in this area and the world's largest IT companies are taking part in it. One of the potential winners is the inconspicuous Canadian company D-Wave Systems, which first started to sell quantum computers commercially in the world.

2. Quantum computer

The history of computers begins in 1945, when, owing to John William Mauchly and John Presper Eckert, the ENIAC [6], considered to be the first general-purpose electronic computer, saw the light of day. Over the years, technological developments in this category have allowed us, among other things, to significantly reduce the size or increase the computing power of these devices. It was not until the 1980s that desktop computers appeared on the market and entered our homes for good. We define, as classical computers, well-known devices which, due to integrated circuits, transistors are able to convert information written in binary form.

The development of today's technology is mainly based on increasing miniaturization and therefore improved speed of operation. The reduction mainly concerns transistors and connections between them. However, this process has its limits and we are unable to minimize them indefinitely. The limits set by the principles of physics indicate that the impassable limit in terms of size is the size of atoms, while the limit for the speed of information transfer is the speed of light in a vacuum. Another issue is that electronic components separate heat that needs to be discharged. All these limitations indicate that in the near future we will reach the end of the possibilities of expanding classical computers.

The basic concept describing the smallest indivisible unit of information in classical computers is the bit. Bit is a logical unit capable of taking one of the two values: zero or one (similarly true or false). In classical computers these values correspond to the voltages on the transistors that make up the logic gates. Instead, the basic unit of information in quantum computing is the qubit, or quantum bit, which is an extended version of its classical variety. This is because it is able to take, apart from the opposite values: zero and one, their combination – called superposition in quantum computer science. Superposition is that a qubit can store both zero and one state at the same time, so it is nondeterministic and the state of the qubit is unknown until it is measured.

The main advantage of a quantum computer over a classical device results from the superposition in question. The computing power of quantum computers grows exponentially with each subsequent qubit used. The greatest profit in the development of quantum technology is due to the enormous possibility of parallelizing calculations. For example, for an n-qubit quantum computer, the number of simultaneously processed quantum states from a given base is 2^n, where an analogous n-bit classical device at a given moment could analyse one n-element determined sequence of zeros and ones.

Over the last few years, we can observe a significantly increasing number of media reports on quantum computers. This is, of course, linked to the intensified work on this technology. Subsequent manufacturers boast about their achievements in this field and try to leave the competition far behind. As this is a relatively new technology on the market, we can see very strong competition. The largest IT companies in the world of Google and IBM, but also smaller start-ups such as Rigetti Computing, are involved in this struggle. The Canadian company D-Wave Systems is the first tycoon in the world to start selling quantum computers. One of the measures that may indicate the achievements achieved so far in the development of quantum computers is the number of cubits owned by them. Table 1 lists the manufacturers, the names of the quantum machines, the number of bits for each of them and the technologies that they use.

It is worth stopping at this point and reflecting on the data collected in the table. It follows that D-Wave has already left competition far behind in 2015. Why can this company boast the number of qubits in its devices several times greater than its competitors have? The Canadian company chose a different path from most of the quantum companies existing on the market.

D-Wave devices use a quantum computing method called quantum annealing. In addition, the company, as well as many others, provides its solutions remotely, available on the D-Wave Leap platform. In addition, the existing services available in the cloud may include, inter alia:

- Xanadu,
- Microsoft Azure Quantum,
- IBM Q Experience,
- Google Quantum Playground.

These platforms allow the development of quantum algorithms with using classic computers. Access through the cloud allows us to test them on real quantum computers. Available solutions allow manufacturers and users to test the development of quantum calculations and also the reliability and correctness of operation of the machines.

Tab. 1. Comparison of the systems

No.	Manufacturer	Device name	Year	Number of cubits	Technology
1	Google	Sycamore	2019	54	Logical gates
2	IBM	Falcon	2019	27	Logical gates
		Hummingbird	2020	65	
3	D-Wave	D-Wave 2X	2015	1152	Quantum annealing
		D-Wave 2000Q	2017	2048	

3. D-Wave computer architecture

The chapter was written on the basis of materials made available by D-Wave. The publicly available documentation includes the most important information concerning, inter alia, the principles of operation, the manner of formulating the problem and the description of updates in the latest versions of the software. A significant part of the current chapter was created on the basis of the user manual "Getting Started with the System" [14].

In quantum computers, the role of processor – CPU (in classical computers) is performed by QPU (Quantum Processing Unit). D-Wave QPUs form the lowest energy states of superconducting rings. Superconducting qubits require a magnetic field for current to flow in both directions simultaneously (these directions symbolize basis states). A qubit is a quantum object so it can be in a superposition of both basis states. The quantum annealing process ends with the transition of quantum bits from superposition to one basis state. This process is visualized in the documentation as shown in Figure 1.

Figure 1 shall be interpreted in accordance with the order of the charts shown therein marked as (a), (b), (c). This is a sequence of changes in the chart over time. We start with the state of the superposition, whose representation is a single minimum value in the first chart (a). Then, in the process of quantum annealing, an amplitude is created that divides the parabola into appropriate base states.

In the chart (b), the left depression corresponds to state zero, while the right depression corresponds to state one. At the end of the process the qubit may be in one of these states. The probability of the cubit being found in both states is equal at 50%. However, this value can be controlled by using an additional magnetic field as shown in the last chart (c). The magnet deflects the chart, increasing the probability of the cubit being found in a lower well. The programmable parameter responsible for controlling this additional magnetic field is the so-called bias, i.e. a certain fixed value. In its presence, the qubit minimizes its energy. We can see the full potential of the qubits when they are coupled and can influence each other. The device used for this operation in the D-Wave QPU is the coupler. This mechanism can force two qubits to stay in the same or opposite states. As in the previous case, the weight of the correlation between conjugated qubits can be changed by software applications. Thanks to programmable values of biases and weights, we are able to define the problem in the D-Wave system. The coupler is therefore the tool that uses a quantum mechanics phenomenon called quantum entanglement. When formulating a task, a user determines values for both of these mechanisms – the bias and the coupler. They define an energy chart similar to that shown in Figure 1. Quantum annealing is about making the D-Wave quantum computer find its minimum value. Devices are becoming more and more complex by adding more qubits. For classical computers, finding the minimum energy of a state is an NP-hard problem, so they cannot solve it efficiently. The Hamilton operator is used to describe the energy of any state in quantum mechanics. Let us consider a very simple example of a system where the object is lying on the table or under the table. Hamiltonian returns the energy value from which the position of an object can be determined. Energy is greater for the object on the table than the energy of the object on the floor.

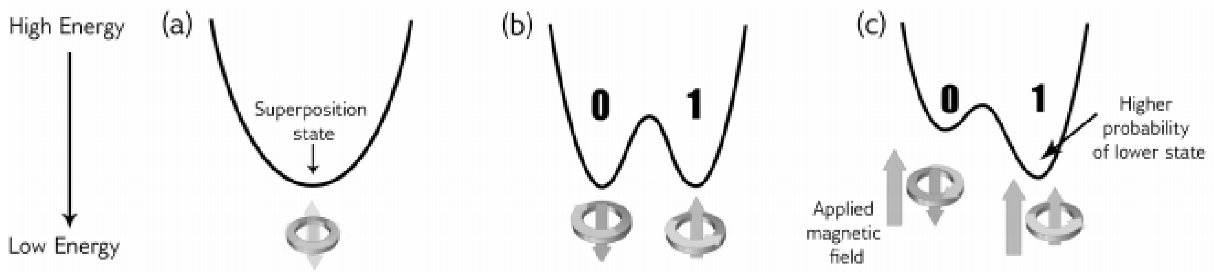

Fig. 1. Quantum annealing (source: documentation "Getting Started with the System")

For a quantum system, a Hamiltonian is the function that maps a specific state called the eigenstate to energy. Only when a system is in the eigenstate of the Hamiltonian is its energy defined and called the eigenenergy. When the system is in a different state, its energy is undefined. The set of defined eigen states creates the eigenspectrum. For the D-Wave system, the Hamilton operator has the form:

$$\mathcal{H}_{ising} = -\frac{A(s)}{2}\left(\sum_i \hat{\sigma}_x^{(i)}\right) + \quad (1)$$
$$+\frac{B(s)}{2}\left(\sum_i h_i\,\hat{\sigma}_z^{(i)} + \sum_{i>j} J_{i,j}\,\hat{\sigma}_z^{(i)}\hat{\sigma}_z^{(j)}\right)$$

where $\hat{\sigma}_{x,z}^{(i)}$ are the Pauli operators on the q_i and h_i qubit. $J_{i,j}$ are the values of the biases of the qubits and the couplings between them. Hamiltonian is the sum of two expressions:

- $-\frac{A(s)}{2}\left(\sum_i \hat{\sigma}_x^{(i)}\right)$ – describes Hamilton's tunnelling phenomenon – it reaches the lowest energetic state when all qubits are in superposition

and

- $\frac{B(s)}{2}\left(\sum_i h_i\,\hat{\sigma}_z^{(i)} + \sum_{i>j} J_{i,j}\,\hat{\sigma}_z^{(i)}\hat{\sigma}_z^{(j)}\right)$ – defines the so-called Hamiltonian problem – expresses the lowest energy state that is the solution to the problem under analysis.

In quantum annealing, the system starts in its lowest energy eigenstate, as represented by the first expression. As it anneals, it introduces the Hamiltonian problem incorporating the mechanisms discussed earlier – the bias and the coupler. At the end of the process, the system is in the eigenstate of the Hamiltonian problem, which is given by the second expression. In the best case, it should be in a minimum energy state throughout the annealing process to ultimately give the response to the problem being solved.

A device for solving mathematical problems in a computing environment is a computational resource called Solver. In this environment, the problem is formulated by specifying its parameters and attributes that control the way it is run. In order to express a computational problem in a form that allows it to be solved by minimization, an objective function is needed that corresponds to the energy of the system examined. In the case where a quantum processor (QPU) is the environment, energy is a function of the binary values representing the qubits. The best solution usually corresponds to the global minimum, i.e. the lowest value of the function in the entire domain. The objective function for quantum processors can take the form of the Ising and QUBO models.

- Ising model – the model used in statistical mechanics. The model is described by discrete variables that can be arranged with a spin up and down, the states correspond to the values +1 and –1. The relationship between spins represented by couplings can be correlated or uncorrelated. The objective function described by the Ising model looks as follows:

$$E_{ising}(s) = \sum_{i=1}^{N} h_i s_i + \sum_{i=1}^{N}\sum_{i=1}^{N} J_{i,j} s_i s_j \quad (2)$$

  where h_i are linear coefficients corresponding to the values of qubit biases, and $J_{i,j}$ are square coefficients corresponding to the coupling forces between them.

- Quadratic unconstrained binary optimization problems (QUBO) are combinatorial optimization problems that have been widely used in economics, finance and computer science. The variables take the values 1 (True) and 0 (False). We define the problem using an upper triangular matrix Q of dimension $N \times N$ and a vector of binary variables x as the minimizing function:

$$f(x) = \sum_i Q_{i,i} x_i + \sum_{i<j} Q_{i,j} x_i x_j \quad (3)$$

  where the diagonal coefficients of the matrix $Q_{i,i}$ are linear and the non-zero non-convex matrix coefficients are quadratic. This can be presented more succinctly as:

$$\min_{x\in\{0,1\}^n} x^T Q x \quad (4)$$

  Furthermore, in scalar notation, the objective function expressed in QUBO form has the form:

$$E_{qubo}(a_i, b_{i,j}; q_i) = \sum_i a_i q_i + \sum_{i<j} b_{i,j} q_i q_j \quad (5)$$

- In addition, the manufacturer in the documentation also mentions graphical methods based on the above-mentioned objective functions.

The topology of the D-Wave quantum processor is to combine qubits in a lattice form. This form is crucial in the process of mapping the problem, which is the objective function presented graphically to the QPU. The qubits are connected to one another by a coupler mechanism. The D-Wave company has developed two ways of connecting quantum bits with one another, it is the older generation architecture Chimera and the newer generation architecture Pegasus, respectively.

The Chimera topology was present in all D-Wave devices until 2017, the last device based on the Chimera graph architecture was the D-Wave 2000Q system. The qubits in the QPU are arranged both vertically and horizontally. The documentation also includes the following two characteristics of the Chimera qubits:

- Nominal Length 4 – each qubit is connected to four orthogonal qubits via internal couplers,
- Degree 6 – each qubit is connected to six different qubits (four from internal connections, two more from external connections).

The architecture based on the Pegasus topology has been used by D-Wave in new systems since 2020. The first, and so far the only, device using the Pegasus system is the D-Wave Pegasus. The system, offering over 5000 qubits, is described by the manufacturer as the most innovative commercial quantum computer in the world [2]. As with the Chimera topology, the qubits are also oriented both horizontally and vertically. In contrast, qubits aligned in a similar way are also shifted in relation to each other. The characteristics of Pegasus qubits are as follows:

- Nominal Length 12 – each qubit is connected to twelve orthogonal qubits via internal couplers,
- Degree 15 – each qubit is connected to fifteen different qubits (twelve are from internal connections, two more from external connections, the last one is provided by an odd coupler).

4. Hardware of the D-Wave computer

The information that has been included in the paper so far concerns the broadly understood processes taking place inside the processor. In computer science, it is common to distinguish between two key terms: software and hardware. We can classify in the first category this quantum annealing process, environments to solve problems or the computation model used. This chapter will describe how the D-Wave system is built from a physical perspective.

The components that make up the system are the processor, the cooling and the means of protection from external influences. The smallest component of a quantum computer is a quantum transistor, also referred to as the *Superconducting QUantum Interference Device*. It is the response of the quantum technology to MOSFET transistors, known from classical computers, building integrated circuits in CMOS technology.

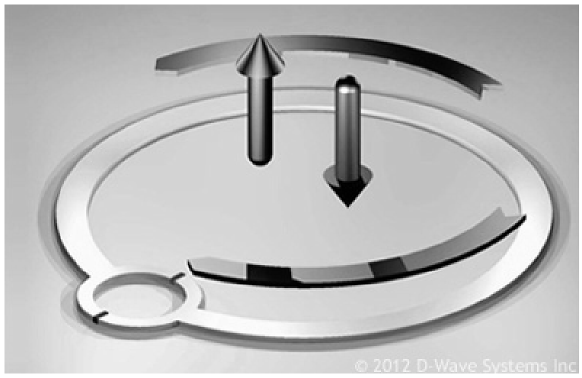

Fig. 2. SQUID

Figure 2 schematically illustrates the structure of this basic structural element of a quantum computer. The occurrence of the quantum effect, preserving the structure as a qubit, is possible due to the properties of the material from which they are made. The large loop in the figure is made of niobium metal. When processing this metal, when it is cooled it becomes a superconductor and begins to exhibit quantum mechanical effects. Using the couplers described in the previous section, qubits are joined into multi-qubit processors. The structure in which interconnected qubits can exchange information is the basis for creating programmable quantum devices. Several additional components are needed for the operation of the processor. A significant part of the circuits surrounding the qubits and couplers is a structure constructed from the Josephson junctions and the control lines. They are responsible for addressing each cubit and storing information in the magnetic element of the memory. In addition, each qubit has a device that is responsible for reading its state after completing the computations. The manufacturer uses well-known methods and knowledge derived from many years of experience in creating semiconductor integrated circuits. The parameters of these solutions are said to be good enough that the QPU modules can be used commercially in them. The next step in building a quantum computer is to separate the QPU from the board and place it inside the system. By means of signal lines, the module is connected to a superconducting logic circuit on the chip.

A key component of a computer is the cooling system. For a quantum processor to operate steadily, it is necessary to lower the temperature of the computing environment below 80 mK. In addition, an increase in productivity is observed with a decrease in temperature. Unfortunately, ensuring such restrictive conditions requires very complicated apparatus, which occupies a lot of space. Most of the computer's physical volume is precisely due to the considerable size of the cooling system – the dilution cooler. The apparatus operates on a principle that uses a significant decrease in temperature during the process of dissolving the helium isotope [1]. In addition, liquid helium circulates in a closed loop system without the need for replenishment. This technology is proven and used in many different areas requiring such low temperatures. The input/output devices of the subsystem are responsible for the bidirectional transfer of information between the user and the QPU. The signals are low-frequency analogue currents transmitted along metal lines, which transform into superconducting lines at low temperatures. Components included in the input/output subsystem include low-frequency filters to remove noise, devices that convert server signals into analogue currents, and an access server that receives instructions from the user. For the system to function properly, most of its components must be made of appropriate materials. The elements must be resistant to low temperatures, made of thin, superconducting metals. Moreover, materials close to the processor must not exhibit magnetic properties. Shielding against electromagnetic RF disturbances is provided by the protective housing of the system. The signals are transferred to the computer via a digital optical channel carrying programming information and computation results. The system and all its components are housed in a cubic housing.

Fig. 3. D-Wave 2000Q

5. Disadvantages and advantages

Understanding the differences in the computational models used by quantum computers requires identifying them. This paper focuses on the device based on the quantum annealing mechanism, detailed in the previous chapter. Nevertheless, it is not the only manufacturer on the market to focus its efforts in the field of quantum computing. Moreover, in addition to the technology developed by D-Wave, there are also other approaches. The best known alternative calculation model is the circuit model. This approach is based on the use of a universal gate model quantum computing. The circuit model is, generalizing it significantly, much more universal. This opinion will be expanded later in the paper, while the mere observation of companies interested in this approach proves its importance. Quantum computers based on the gate model are developed by the world's largest IT companies.

We can also distinguish one more type of computers, which in a rather figurative way we can call quantum computers. These devices should be viewed as computers inspired by quantum technology. This means that we use quantum algorithms in them to solve the problem, but qubits are not used in the process.

Two basic methods of quantum computing are therefore distinguished: the circuit model and quantum annealing. Although these approaches appear to be completely different, their common part is not an empty set. Both methods are based on a similar concept involving the use of qubits. They are useful for various tasks and various types of problems, and face different challenges in their design and production. Both models offer different perspectives on practical applications of quantum computing.

- The circuit model is based on the creation of quantum structures with using stable qubits. Maintaining their stability is problematic, and the situation is getting worse as their numbers increase. As a result, computers with universal quantum gate models are limited to laboratories for the time being.
- The quantum annealing model focuses on solving optimization problems and is less prone to noise. This allows for more efficient use of qubits, and thus for obtaining more parameters for specific problems [8].

Despite the differences, the gate-based quantum computing method and quantum annealing are somewhat equivalent. The circuit model is able to simulate any Hamiltonian with a finite number of quantum gates and therefore perform adiabatic quantum computations. Quantum annealing devices are equivalent to gate-based quantum computers under certain conditions. They must use Hamiltonians in which all elements except the diagonal in the standard base are real and non-positive. Both methods of quantum computation are equivalent, but under certain circumstances they are not always satisfied [7].

As an introduction to the pros and cons of D-Wave's move away from the circuit model, we must point out that we are talking about the technology of the future. The field of quantum computing is constantly evolving, so many advantages and disadvantages may change as research progresses.

After all, the potentially biggest benefit of using a quantum annealing model is the class of problems it can solve. D-Wave devices solve problems formulated in the form of optimization problems. Optimization problems constitute most of the problems of today's world. Quantum annealing is great at optimizing solutions by quickly searching through large sets and finding the minimum value. The latest Google announcement stated that the D-Wave machine is over 10^8 times faster than simulated annealing running on one core of a classical computer [7]. Quantum annealing works better than classical computational methods to solve some optimization problems. Furthermore, if we are actually able to present the problem in the form of an optimization task, the number of bits may be much higher than in the case of systems using a circuit model. The quantum annealing mechanism is more resistant to noise than its direct competition. The greatest practical advantage is that this technology is already commercially available today. Quantum computers using circuit models, on the other hand, are at a much earlier stage of research, and their applications and destination are currently only in the laboratory. The method used by D-Wave can already compete with classic computers and start solving real problems.

Scientists from the pharmaceutical company GSK decided to investigate whether the existing quantum computers could already help in the discovery of medicaments [9]. Scientists examined the effect of quantum computing on codon optimization, i.e. the genetic sequence of nucleotides in the DNA chain which such sequence codes for a single amino acid in a protein [5]. Using the Binary Quadratic Model (BQM) quantum algorithm, which can run on various quantum platforms, the team decided to test the D-Wave quantum annealing method and an IBM gate-based quantum computer. The test device representing the Canadian company was their most advanced Pegasus system with over 5000 cubits of power. The IBM quantum computer using the circuit model had only 24 qubits. The D-Wave system was able to map 30 amino acids. The result is satisfactory, sadly still comparable with classical algorithms. On the other hand, the device based on the circuit model had highly variable performance and often returned incorrect results. Ultimately, the result was significantly lower and amounted to four amino acids only. So the D-Wave quantum processor is already making progress in solving real problems. The next comparison will only be fair if devices like IBM catch up with hardware scaling.

We have therefore received a number of advantages potentially deriving from D-Wave using the quantum annealing model. Unfortunately, these devices are not without flaws. The disadvantages result directly from the advantages of devices based on the circuit model. The capabilities of quantum computers using gates are much wider. A system based on a circuit model consists in building stable cubits containing basic quantum operations. These operations may be combined to create any sequence that allows the activation of increasingly complex algorithms. The best known flagship ones include Shor’s factorization algorithm and Grover’s database search algorithm. These algorithms and many others will be able to run on a quantum computer with a circuit model. Gateway-based devices can therefore be used for many other problems. The versatility of the circuit model is much greater than, having specific use cases, the quantum annealing method [12]. Moreover, due to the early phase of the work on the error correction protocol, the benefit of the increase in the number of qubits is not obvious.

Based on the collected information, you can try to answer the question: Which method is better? The answer is neither simple nor unequivocal. It will depend mainly on individual needs. Both the quantum annealing and gate-based models of quantum computing are still under intensive development. It is hard to make an unambiguous decision, which of the methods will be better in the long term. At the present time, however, it is quantum annealing that has reached a level of development allowing it to be applied in a realistic manner. D-Wave devices have already hit the commercial market and there are initial reports of their superiority over classic computers. This is undoubtedly the greatest advantage of this technology compared to the circuit model. Although optimization tasks are the main problem facing the world today, they are not the only hardships. Therefore, quantum annealing will not be able to replace or eliminate the circuit model. The gate-based device is considered to be the only one that can bear the full title of a quantum computer. Their potential applications are much wider, and achieving the claimed quantum supremacy would revolutionize the field of quantum computing. D-Wave, on the other hand, should not be afraid of devices based on the circuit model. This is because they are not in direct competition, they are created for other purposes and although they have the ability to solve optimization problems, this is not their only advantage. Another argument in favour of quantum annealing is that the number of qubits currently used differs significantly from the competitive circuit model. These devices should not be regarded as truncated versions of quantum computers, capable of resolving a specific type of task. There are many problems that can be solved by using quantum annealing.

6. Controversies

There has been much controversy surrounding D-Wave's devices and the solutions it uses. The field for discussion is primarily related to the adopted model of adiabatic quantum computing. It is accused of using a simulated mechanics and not a quantum annealing. Another controversial issue remains the limited scope of the problems that can be solved. According to many world experts on quantum computers, the lack of universality of this type of devices excludes the possibility of calling them “truly quantum computers”. The goal to be achieved is a general-purpose quantum computer that would solve quantum error correction problems, significantly exceeding the capabilities of currently used supercomputers. The competition in the quantum computing market is, of course, a completely different issue. Many doubts could arise as a result of the dirty game of competing companies. Nevertheless, the existence of many controversies may actually be justified, so the most important ones are discussed later in the paper. Each of them is based both on the technical properties and subjective feelings of the evaluator.

D-Wave describes the devices it has built as the world's first quantum computers, which are the future of mathematical computing. Many of the world's experts view this fact in a completely different way. Research presented by the University of Southern California shows that D-Wave devices are closer to actually being called quantum devices. Researchers showed that the machine did not use the simulated annealing model as originally alleged. In addition, the quantum annealing model has been proven to work in the quantum sphere and there is a strong correspondence between it and the way the D-Wave system works. Nevertheless, no clear answer was given, leaving room for doubt. Daniel Lidar, the research leader, says that while his team has not shown this, D-Wave likely uses quantum annealing. However, the conducted research does not indicate that devices based on this model can be described as quantum computers. They are not universal enough to solve every possible problem.

The most frequently pointed out disadvantage of the D-Wave device is its lack of universality. However, the company is aware that the device has the limitations. The company believes that its devices are the milestone on the way to building a real quantum computer. D-Wave is also considered a pioneer of the superconducting technology. The semiconductors developed by them emit practically no heat and theoretically may constitute an extension of Moore's law. Computers created by D-Wave, despite many potential application areas, are not what many supporters of quantum technology have been waiting for. Quantum technology owes its greatest publicity not to the devices themselves, from a technical point of view, but to algorithms. However, the quantum computer developed by D-Wave was not designed with algorithms in mind. It can solve a very specific type of problems. This is an advantage as mentioned earlier, but also a disadvantage. This feature is a controversial element on which most of the controversy around the solutions used arose. Among the most recognized quantum algorithms, which, unfortunately, cannot be presented at a given moment in a form that allows them to be solved using a D-Wave device, we can include: the Shor algorithm and the Grover algorithm.

A lot of controversy arose on the occasion of the premiere of the D-Wave Two system in 2013. The company was accused of ignoring the problem of quantum decoherence. The problem is the loss of a state of the quantum qubit due to the interaction of the object with the environment. D-Wave has received support from independent scientific studies that showed the D-Wave machines used both superposition and entanglement. Decoherence was to cause the loss of the quantum state by qubits and the elimination of entanglement of the quantum system. The process was therefore supposed to cause errors in the computations. The discussed D-Wave Two device had a power of 512 qubits. Research has shown that at that time the system did not perform better than the best classical computing algorithms. This also applied to problems ideally suited to adiabatic quantum computing. The head of research at the Lockheed Martin Quantum Computing Center claimed that if D-Wave can handle the problems of decoherence and error correction, their system will be able to outperform the best classical alternatives [3]. This advantage was achieved, as indicated by the study [11] conducted in 2016 with using the D-Wave 2X device equipped with 1152 cubits. The study compared the simulated annealing methods, the quantum Monte Carlo method and the quantum annealing method. The D-Wave 2X device achieved significantly better results compared to the simulated annealing method running on a single processor core. For a test instance with 945 variables, D-Wave was found to be about 10^8 times faster with a 99% success probability. The quantum annealing algorithm compared to the quantum Monte Carlo method emulating quantum tunnelling on classical processors repeated the result, giving a speedup of 10^8 times better over time.

Many questions about the controversy surrounding D-Wave computers also appear on popular Q&A sites. University of Michigan professor Igor Markov took his position on the D-Wave devices. The professor, a former Google employee, listed the following controversial elements in his opinion:

- The evidences provided by D-Wave are not convincing. Based on the D-Wave Two documentation, both quantum effects and a significant amount of non-quantum noise can be seen.
- D-Wave employees publicly made claims that were at best misleading. Their materials show gaps in understanding the basic principles of computer science. In addition, they indicate which information is relevant and which can be ignored.
- The scientific studies supporting D-Wave's claims tend to be opportunistic and are often disproved. Studies with negative conclusions on D-Wave are better justified and more convincing.
- Many respected scientists with great achievements in the field of quantum computing support D-Wave for private reasons. They take care of the field for conducting research activities.
- The D-Wave approach to quantum computing seems very hostile to quantum error correction, which many researchers consider necessary for such devices.

Much of the above-mentioned elements can clearly be classified as Professor Markov's personal feelings, nevertheless many scientists agree with his opinion. Ultimately, it is worth noting that D-Wave is a private organization, so its goals are different from that of the scientific community. While the research community is demanding progress in this area, the company's motive is primarily return on shareholder investment and overall profit.

7. Conclusion

The area of the article included the computer architecture, the advantages and disadvantages of the computational method used compared to the circuit model, and the controversies arising around the solutions used. The D-Wave system, which arouses much controversy, was subjected to a wide analysis. The architecture of the device and the quantum annealing method used have been described in detail based on the manufacturer's documentation. In addition, the computational method used in the D-Wave system was compared with a competing circuit model. The combination of both methods allowed to work out the advantages and disadvantages of each of them and to present potential applications. The background of controversial papers and discussions appearing on the web was examined. Their legitimacy was assessed as objectively as possible. Ultimately, it should be noted that the field of quantum computing is in a stage of intensive development so all the advantages and disadvantages and controversies mentioned may change to the opposite over the years. The paper can serve as a kind of basic compendium of knowledge about D-Wave devices.

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Komputer kwantowy D-Wave – zalety i wady odejścia od modelu obwodowego

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Artykuł powstał na podstawie pracy dyplomowej o takim samym tytule. Celem pracy jest analiza urządzeń firmy D-Wave wykorzystujących efekty kwantowe. Badania skupiają się na wykazaniu wad oraz zalet odejścia przez przedsiębiorstwo od modelu obwodowego w swoich komputerach. Przedmiotem badań jest wykorzystywany adiabatyczny model obliczeń kwantowych bazujący na mechanizmie kwantowego wyżarzania. Badania opierają się na publicznie udostępnionej, obszernej dokumentacji firmy D-Wave Systems. Na podstawie artykułów naukowych, konferencji oraz informacji zawartych w serwisach internetowych opisane zostały kontrowersje, wady oraz zalety przyjętych rozwiązań.

Słowa kluczowe: D-Wave, komputer kwantowy, kwantowe wyżarzanie

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