Optimization of Manufacturing Equipment Layouts in Factories Employing Quantum Computer

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The shrinking labor force and the market's demand for reduced manufacturing costs are forcing the manufacturing industry to improve productivity even further. OKI is developing a method to solve this problem using a quantum computer. This article describes the developing method's application to the optimization of equipment layout at a LED Management Factory belonging to OKI Data, OKI Group's printer business company.

Background

Due to the mid-to-long term reduction in Japan's working population, labor shortage in the manufacturing industry has become a major social problem. According to a survey conducted by the Ministry of Economy, Trade and Industry, labor shortage is apparent in 94% or more of both large and small-to-medium-sized companies and 32% of the companies claim the problem is impacting their business[1]. Since a drastic and swift resolution of the labor shortage is difficult, productivity improvement is the only way to deal with the problem for the time being. Furthermore, the globalization of the market exposes most manufacturers to intense international competition, and manufacturers who are not cost-competitive are weeded out. Requirement here is the lowering of manufacturing costs by reducing waste to an absolute minimum, and productivity improvement again becomes important.

Productivity improvement of manufacturing sites is nothing more than reducing cost and time by optimizing schedules and arrangements of manufacturing resources (workers, manufacturing equipment, raw materials, etc.), and the product mix ratio. Process of finding an optimal combination from a large number of options under various constraints is generally called a "combinatorial optimization problem." There are many combinatorial optimization problems that must be solved at a manufacturing site. That is, productivity improvement can be expected by solving these combinatorial optimization problems. However, in the actual field, the variables to be combined are numerous, and the number of combinations explodes accordingly. Therefore, many problems were too difficult to solve with conventional Neumann computers. Quantum computers are expected to solve this issue.

Quantum computers are massively parallel computers that utilize quantum mechanics. Due to the overwhelming computing power expected over conventional computers, they are being actively developed throughout the world. In Japan, quantum technology including quantum computers is positioned as an important core technology, and the government is accelerating the technology's research and development[2].

There are mainly two types of quantum computers, the gate-based and the annealing-based. The gate-based is expected to be capable of general-purpose calculations. In 2019, Google surprised the world by announcing its development of a 53-qubit gate-based quantum computer capable of outperforming supercomputers[3]. However, there are many technical challenges that need to be resolved for adequate performance, and it will take some time before it can be put to practical use.

On the other hand, the annealing-based quantum computer (hereinafter, quantum annealer) is a quantum computer specialized for calculation of combinatorial optimization problems. Since it is simpler to implement than the gate-based, quantum annealer with relatively large number of qubits has been developed. In 2014, D-Wave[4] of Canada launched the world's first commercial remote access service of a quantum annealer. This enabled users to use the quantum annealer without purchasing large and expensive hardware, and instantly raised anticipation for its practical use.

Under such circumstance, OKI is researching and developing an application technique using a quantum annealer to solve various social problems, including those of the manufacturing industry previously mentioned. In order to perform an in-house verification of the basic calculation technique that was established, the technique was applied to the problem of optimizing the equipment layout at OKI Data's LED Management Factory[5]. The details are described in the sections below.

Optimizing Factory Layout

At OKI Data's LED Management Factory, multiple products with different manufacturing processes are manufactured by sharing dozens to hundreds of different semiconductor manufacturing equipment and workers moving between equipment. In order to improve productivity, it is necessary to optimize the layout of the equipment and shorten the moving distance (hereinafter, flow line) of the workers. There are about 10^{76} combinations of equipment layout, and even using high-performance computers, it will take 10^{51} years to evaluate them all. Below, the description of the problem to be solved will be explained first, followed by the procedure for solving the problem using a quantum annealer. At the end, the obtained results will be presented.

(1) Problem Description

At the factory, the worker uses the same equipment group to process parts and manufactures multiple products. The manufacturing process differs for each product, but many pieces of equipment are shared. The manufacturing process describes the order of the processes when manufacturing a product and the equipment used in each process. The worker processes the part in accordance with the manufacturing process, and when the process is completed, moves to the equipment used in the next process and begins another process. One product is finished when the all manufacturing processes are completed.

Figure 1 is an overhead view that schematically shows the layout of the factory. The factory is made up of a number of small areas called bays. Inside a bay, there are many types of equipment for processing parts. The space where the equipment is placed is called a slot. The bays and the equipment in the bays are connected by passages, which the worker can move about freely.

The problem on hand is to optimize the equipment layout and shorten the flow line to complete one product as much as possible. Since multiple products are to be manufactured, the evaluation index will be the average value of the flow line for each product. Since it is possible to shorten the overall flow line by shortening the flow line of the more often manufactured product, the distance of flow line will be weighted-averaged with the production lot ratio of each product.

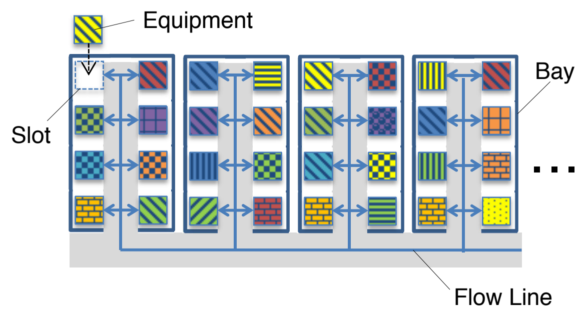

Figure 1. Factory Layout

(2) Calculation Method

Quantum annealer is a device that experimentally finds the spin variable that minimizes the energy of the statistical mechanical model called Ising model[6]. Therefore, in order to solve the combinatorial optimization problem using a quantum annealer, it is necessary to formulate the problem in question with an Ising model or an equivalent model called QUBO (Quadratic Unconstrained Binary Optimization). The energy function of the QUBO is given in equation (1).

$$E(\boldsymbol{x}) = \sum_{i<j} J_{\mathrm{ij}} x_i x_j + \sum_i h_i x_i \tag{1}$$

QUBO variable x is a binary variable that takes on a value of 0 or 1. A quantum annealer can be rephrased as a device that finds the value of the variable x that minimizes the energy function E with J_{ij} and h_i as input parameters.

First, how to define the QUBO variable is considered. The target to be calculated is equipment layout, that is, which equipment is placed in which slot. It is convenient to use the calculation target as the variable since the answer can then be directly obtained. Therefore, the QUBO variable is defined by equation (2).

$$x_{s,d} = \begin{cases} \text{1: Place equipment } d \text{ in slot } s \\ \text{0: All others} \end{cases} \tag{2}$$

Next, the variable $x_{s,d}$ is used to express the objective function (distance of flow line) in the QUBO model. In doing so, the value of the variable calculated by the quantum annealer for which the energy function is minimized will match the equipment layout that provides the shortest flow line. The energy function for the problem is shown in equation (3).

$$E(\boldsymbol{x}) = \sum_{u,t,s',s''} x_{s',d_u[t]} \cdot x_{s'',d_u[t+1]} \cdot L(s',s'') + \sum_{s}\left(\sum_{d} x_{s,d} - 1\right)^2 \cdot p + \sum_{d}\left(\sum_{s} x_{s,d} - 1\right)^2 \cdot p \tag{3}$$

In the equation, s' and s" are slots in which the equipment used in process t and t+1 are placed, respectively. L(s', s") is the distance between s' and s", $d_u[t]$ is the equipment used in process t of product u, and p is a penalty coefficient. The first term in equation (3) represents the objective function to be minimized, that is, the flow line distance. The second and third terms represent constraints. The constraints here are basic conditions that 1) each slot must hold one equipment and 2) each equipment must be placed in a slot. The second and third terms correspond to constraints 1) and 2), respectively. The strengths of these constraints are adjusted by parameter p. If p is too large, the constraints will be satisfied, but it will be difficult to obtain a good solution that shortens the flow line. On the other hand, if p is too small, the probability of obtaining a solution that does not satisfy the constraints increases. Therefore, it is necessary to set proper parameter values through appropriate experimentations.

Finally, equation (3) is expanded and converted into the form of the QUBO model's equation (1). The calculation parameters J_{ij} and h_i are obtained and entered into the quantum annealer for calculation. Since the variables to the problem on hand were numerous and exceeded what the quantum annealer can calculate at once, the problem was divided and repeated calculations were performed. The time required for converging on a solution to some extent was about 30 minutes. The solutions output from the quantum annealer (values of $x_{s,d}$) are thoroughly examined for validity, and the solution determined to be valid ultimately becomes the optimized equipment layout.

(3) Calculation Results

The quality of the solution was evaluated by comparing the calculated results against the equipment layout before optimization (current equipment layout).

Results of the calculated flow line distance before and after optimization are shown in **Table 1**.

Table 1. Calculation of Flow Line Distance

(a) Lot Ratio (Product 1) : (Product 2) = 1 : 4

	Before Optimization	After Optimization	Change
Product 1	1,510	1,284	-15%
Product 2	2,876	2,036	-29%
Average	2,603	1,886	-28%

(b) Lot Ratio (Product 1) : (Product 2) = 1 : 1

	Before Optimization	After Optimization	Change
Product 1	1,510	961	-36%
Product 2	2,876	2,307	-20%
Average	2,193	1,634	-21%

(c) Lot Ratio (Product 1) : (Product 2) = 4 : 1

	Before Optimization	After Optimization	Change
Product 1	1,510	832	-45%
Product 2	2,876	2,484	-14%
Average	1,783	1,162	-24%

Since the distance is standardized, the unit is arbitrary. Two products were manufactured (Product 1 and Product 2), and calculations were carried out using three lot ratios of (a) 1:4, (b) 1:1 and (c) 4:1. It can be seen that the flow line distance is shortened by optimizing the equipment layout for both products 1 and 2, regardless of the lot ratio. It can also be seen that the layout is calculated so that the flow line of the product with the larger lot is more intensively reduced. A look at the averaged results by lot ratio reveals that optimization has achieved a flow line reduction of 20% or more for all lot ratios.

The above results confirm that, 1) equation (3) correctly formulates the layout optimization problem into the QUBO model, 2) the quantum annealer outputs a solution that minimizes the model energy, and 3) significant flow line improvement can be achieved through optimization.

Conclusion and Future Outlook

Optimization of manufacturing equipment layout in an actual factory employing quantum annealer was demonstrated. The real-life problem was formulated into an equation, which was then calculated with a quantum annealer. As a result, the layout that can reduce the flow line by 20% or more on average was successfully calculated. However, as mentioned earlier, the number of variables in the problem was too large for the quantum annealer to calculate at once. Therefore, the problem was divided and repeated calculations were performed. Since the calculations were discontinued after finite time, the obtained solution is considered to deviate from the true optimal solution. This tendency is expected to become more prominent when solving problems that are larger in scale than the one presented in this article. While anticipating the hardware performance of the quantum annealer to improve, it is necessary to study efficient methods of obtaining near-optimal solutions such as task sharing with classical computers and division of problems. These are the technical issues that have emerged through this trial.

OKI will challenge these technical issues and contribute to solving social problems such as improving productivity to remedy labor shortages.

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TIPS 【Glossary】

Quantum computer
A generic term for computers that use quantum-mechanical states (superposition of 0s and 1s) as information processing units (qubits). It can be classified into a gate-based that can perform general-purpose operations and an annealing-based that specializes in solving combinatorial optimization problems.

Quantum annealer (annealing-based quantum computer)
A computer specializing in deriving an optimal combination by utilizing the superposition of qubits and the coupling between qubits.

Ising model
A statistical mechanics model representing the properties of a magnetic substance, which is composed of spins that have two states, upward or downward.