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# A Quantum Annealing Solution to the Job Shop Scheduling Problem with Availability Constraints

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## 1 Introduction

Quantum optimization is an emerging and fast developing research field. It consists in using quantum computers and algorithms to tackle NP-Hard problems. This generally requires formulating the problems as Quadratic Unconstrained Binary Optimization (QUBO) models. While current quantum computers are limited in the number of qubits and thus in the number of variables they can handle, it is challenging to build efficient models for optimization problems that integrate practical constraints. The first quantum annealing solution for the job shop scheduling problem with the makespan objective was developed in [4]. The proposed model was extended to the flexible job shop scheduling problem in [3].

We consider in this paper the job shop scheduling problem with availability constraints. We propose a quantum annealing solution for both cases where unavailability periods are fixed and flexible. We first present a mathematical formulation of the job shop scheduling problem as a QUBO model [1]. Then, we show how to integrate the availability constraints to this model. Results of numerical experiments made on the D-Wave quantum annealing computer show the efficiency of the approach.

## 2 Problem definition

The job shop scheduling problem with availability constraints can be stated as follows : A set of  $n$  jobs  $J = \{J_1, J_2, \dots, J_n\}$  has to be processed on a set of  $m$  machines  $M = \{M_1, M_2, \dots, M_m\}$ . Each job  $J_i$  consists in a linear sequence of  $n_i$  operations  $(O_{i1}, O_{i2}, \dots, O_{in_i})$ . Each machine can process only one operation at a time and each operation  $O_{ij}$  with a processing time of  $p_{ij}$  time units needs only one machine. There are  $k$  unavailability periods  $\{h_{j1}, h_{j2}, \dots, h_{jk}\}$  on each machine  $M_j$ . Two cases are considered in the paper : either the starting date  $S_{jk}$  of unavailability period  $h_{jk}$  of duration  $p'_{jk}$  is known in advance and fixed, or it is flexible and can vary within a time window. The objective is to determine the starting date  $t_{ij}$  of each operation  $O_{ij}$  so that the makespan noted  $C_{max}$  is minimized. The job shop scheduling problem with availability constraints is strongly NP-hard since the 2-machine flow shop scheduling problem is strongly NP-hard [2].

## 3 QUBO formulation

The following QUBO models the total completion time in a job shop with the Objective function (1) to minimize with 3 multipliers,  $\lambda_1$ ,  $\lambda_2$ , and  $\lambda_3$ , balancing the relaxation of the processing, resource and precedence constraints, respectively.

$$\sum_j \sum_t t.x_{n_i}^t + \lambda_1 \sum_j \sum_i (\sum_t x_{ij}^t - 1)^2 + \lambda_2 \sum_{(i,j,t) \cup (i',j',t') \in T1} x_{ij}^t x_{i'j'}^{t'} + \lambda_3 \sum_{(i,j,t,t') \in T2} x_{ij}^t x_{i+1j}^{t'} \quad \text{with :} \quad (1)$$

$$T1 = (i, j, t) \cup (i', j', t') : i, i' = 1..n_i, j, j' = 1..n, (i, j) \neq (i', j'),$$

$$M_{ij} = M_{i'j'}, (t, t') \in T^2, 0 \leq t' - t < p_{ij}$$

$$T2 = (i, j, t, t') : i = 1..(n_i - 1), j = 1..n, (t, t') \in T^2, t + p_{ij} > t'$$

The boolean variable  $x_{ij}^t$  takes the value 1 if the operation  $i$  of the job  $j$  starts in period  $t$ , with  $i = 1..n_i, j = 1..n, t = 1..T$ , and takes the value 0 otherwise.  $M_{ij}, i = 1..n_i, j = 1..n$ , is the required machine for the operation  $i$  of the job  $j$ .

## 4 Managing fixed and flexible unavailability periods

We apply a pre-processing on the two types of availability constraints.

For cases where the non-availability windows of a machine are known in advance, meaning we already know the periods during which no production operation can be performed, we treat each of those non-availability period as a single operation that has already been scheduled. Then, for each constraint of this type, we create a new job consisting of one operation for which the starting date is fixed.

In cases where the non-availability periods of a machine are unknown, we want to minimize an 'extended' makespan. Indeed, if we only consider the makespan as the objective function, the non-fixed period of non-availability might be scheduled after all the production operations are finished (or at a time it does not penalise the operations). Therefore, the problem becomes more meaningful if we consider that all operations and all non-availability constraints must be completed as soon as possible. To manage such new constraints, we create a new job consisting of one operation for which the starting date is  $S_{jk}$ . Since we minimize the sum of the ending time of each operations, we can easily integrate the new operations resulting from the non-fixed non-availability periods.

We can thus address both types of non-availability in the same problem by creating new jobs consisting of a single operation and by fixing the starting date if the related period of non-availability is known.

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