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DISJUNCTIVE PROGRAMMING - TABU SEARCH FOR JOB SHOP SCHEDULING PROBLEM

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A scheduling helps to reduce the production time which indirectly reduce the costs as well. In job shop scheduling, it does not have a fixed sequence of operations and has a wide range of possible schedule that can be arranged. Our objective is to determine the job order on the parallel machine and minimizing the makespan of the processing time. A tabu search (TS) algorithm has been implemented to solve the job shop scheduling problem. Disjunctive programming (DP) with shortest total and longest total processing time has been used to find the initial solution for TS method. A comprehensive testing on the comparison of the results on different tabu list length with the benchmark values is conducted to investigate the performance of the proposed approach. From the results, DP produces a good result in job shop scheduling problem at least with a gap of 0.53% from the benchmark problem

***Keywords*:** job shop scheduling, tabu search, disjunctive programming, makespan

1. Introduction

In manufacturing, scheduling helps to reduce the production time which indirectly reduce the costs as well. Besides, advantages of scheduling include reducing changeover time of the process, reducing inventory, improving production efficiency, minimizing the scheduling effort as well as providing the real time information. There are different types of scheduling problems. The common types include open shop (Hosseinebadi et al., 2019), flow shop (Ruiz et al. ,2019) and job shop scheduling (Zhang et al., 2017).

In open shop scheduling, the order in which the jobs are performed in the operation is in an arbitrary order. In flow shop scheduling, the order in which the jobs are processed on each machine is fixed. For example, a shoe must undergo the stamping process before going to sewing process and every shoes undergo the same process sequence. As a contrary to the flow shop scheduling, job shop scheduling does not have a fixed sequence of the operations. The jobs are not necessary to pass through all the machine and every job have their specific process sequence. However, each of these scheduling problems still has some similarities. They consist of operations and they will perform jobs. The operations can be done on either one of the machines in a condition that each of the machine can only perform one operation at a time. All the operations have their own time frame.

This research focuses on the job shop scheduling problem which has a wide range of possible schedule that can be arranged. Some of the applications comprise of air traffic control, railway scheduling and flexible manufacturing. Many methods have been used to solve this kind of problem which include tabu search, shifting bottleneck heuristic and simulated annealing. All of these methods are aimed to find an effective way to schedule the jobs to be processed on the machines.

2. Job Shop Scheduling (JSSP)

In job shop scheduling, several machines will process multiple jobs. Each job will have a series of tasks performed in a specific order in which each task is being processed on a particular machine. The main function of JSSP is to arrange the schedule according to the objective function, for instance, minimization of the schedule's length. The schedule's length is denoted by the time of the jobs is being processed from beginning to the end, where all jobs have been completed. There are some constraints and assumptions (Moghaddas & Houshmand, 2008) that should be taken into account for JSSP as shown in Table 1 below.

Table 1: Assumptions and Constraints

No.	Assumptions and Constraints
1.	Each job has its specific order on *m* machine. Alternate routes are strictly prohibited.
2.	The shop should only consist one machine of each kind.
3.	All jobs have their known and constant processing time.
4.	At time zero, all jobs are accessible to be processed on machine. However, if some jobs may not available at time zero due to the agility of the decision variables, it is easier to add the related constraint to the model.
5.	A machine can only process one task on any job at a time.
6.	A task of a job is only allowed to be processed on a single machine.
7.	An operation once started, must run to completion and there must be no interruption during the process.
8.	Pre-emption is prohibited.
9.	The task of a job can only be started after its previous task is completed.
10.	Machine breakdown is not considered since there is continuous availability of each machine on the production.
11.	The limits on resources are not considered except for the machines or workstations.
12.	All the machines are different (not identical) and the operations performed on them are varied.

Disjunctive graph has been widely used in JSSP to formulate the problem. According to Pinedo (2008), disjunctive graph is a directed graph $G = (N, A \cup B)$ where N represents the set of vertices corresponding to each task, (i, j). Figure 1 shows an example of disjunctive graph. From Figure 1, both vertices S and E are dummy nodes that depict the start and end of the operation. A is a set of conjunctive arcs between (i, j) and (k, j) which represents the same job undergoes the consecutive operations. In this case, job j is processed on machine k only after it is been processed on machine i. The plain arrows refer to the conjunctive arc. Meanwhile, B represents a set of disjunctive arcs such that tasks that operate on the same machine are connected with a pair of disjunctive arcs in opposite direction. Disjunctive arcs are shown in Figure 1 as the dashed arrows. To generate a feasible schedule, the disjunctive arcs will be oriented to get a graph that is acyclic which means that there is no closed path and repeated vertex at each path.

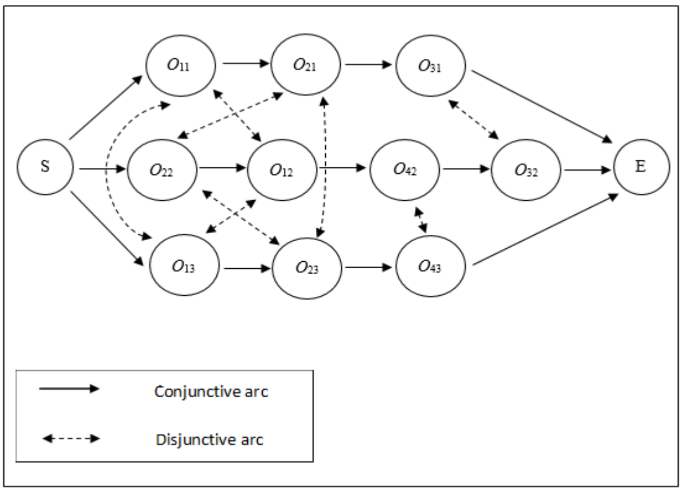

Figure 1: Disjunctive Graph

Noted that, in complexity theory, a problem can be classified into three classes, which are *P*, *NP* and *NP*-complete. The *NP*-complete problems are regarded as hard problem. Scheduling problem is an NP-complete problem and commonly known with its difficulty to be solved (Nordin & Cacetta, 2014). This can be seen in the 10 jobs by 10 machines problem instance by Muth and Thompson (1963) that cannot be solved previously for a time period that exceeds a quarter of a century. Even at the present time, problem instances of 20 x 20 are still hard to be solved optimally. Tabu search is used in this study to solve this JSSP.

3. Tabu Search

Tabu search is a metaheuristic method with the purpose to solve the general optimization problem by obtaining a solution that is close to the global optimum. This method is first discovered by Glover (1986). Tabu search make use of its search memory to prevent itself from cycling and to prevent it stuck in the local minima. Hence, the tabu list is significant as it acts to keep track the previously viewed solution. With tabu list, the search is thus focuses the search on the solutions that is not in the tabu list and the best current solution will be selected from this set of solution, known as allowed set by Blum and Roli (2003) at each iteration. After that, this newly found best solution will be added as one of the member of tabu list. The search is continue until it reaches the specific stopping criterion. However, sometimes the tabu list is too powerful that it forbids some moves that may lead to a better solution. Thus, an aspiration criterion is implemented in tabu search to prevent this kind of situation. The aspiration criterion will considered the certain moves if the moves will lead to a better result.

The memory of tabu search generally divided into three types of memories known as short term memory, medium term memory (intensification) and the long term memory (diversification) (Talbi, 2009). The short term is typically used as tabu list in tabu search in which it will temporary store a certain number of previously viewed solutions and the list will be constantly updated for each iteration. The medium term memory keeps the best solution and control the intensification during the search process (Vasant, 2012). In addition, the long term memory save the information of the solutions that have been visited and utilize this information to discover the unvisited part in the search space. In other terms, the long term memory diversify the search to unvisited areas on the search space.

Gendreau (2003) had shown a general template of tabu search with the objective function to minimize the function, $f(s)$. The notation and the template is stated below.

Notation

s	current solution
s^*	best known solution
f^*	value of s^*
N(s)	neighbourhood of s
$\tilde{N}$(s)	permissible subset of $N(s)$

Initialization

Select or build an initial solution s_0.

Set $s := s_0$, $f^* := f(s_0)$, $s^* := s_0$, $T := \emptyset$.

Search

While *termination criterion not satisfied* do

- select s in $\underset{s' \in \tilde{N}(s)}{argmin}[f(s')]$;
- if $f(s) < f^*$, then set $f^* := f(s)$, $s^* := s$;
- record tabu for the current move in T;

Endwhile.

The elements of tabu search are discussed in the following sub-sections.

3.1 Initial solution

The initial solution initializes the tabu list which subject to change at each iteration. Jain et al. (1996) discovered that a good initial solution will provide better solution quality in tabu search. In this paper, disjunctive programming (DP) will be used, together with shortest total processing time (STPT) and longest total processing time (LTPT) rules.

The variable and notations below define the formulation of disjunctive programming. The disjunctive model shown below is based on Pinedo (2008).

Variable

y_{ij} start time of job j on machine i

Notations

A set of conjunctive arcs between task (i, j) and (k, j)
N set of vertices corresponding to each task (i, j)
i,k index of machine
j index of job
p_{ij} processing time of job j on machine i
m number of machines

$$\text{Min } C_{max} \tag{1}$$

subject to

$$y_{kj} - y_{ij} \geq p_{ij} \qquad \forall (i, j) \rightarrow (k, j) \in A \tag{2}$$
$$C_{max} - y_{ij} \geq p_{ij} \qquad \forall (i, j) \in N \tag{3}$$
$$y_{ij} - y_{il} \geq p_{il} \text{ or } y_{il} - y_{ij} \geq p_{ij} \qquad \forall (i, l), \forall (i, j),\ i = 1,\ldots,m \tag{4}$$
$$y_{ij} \geq 0 \qquad \forall (i, j) \in N \tag{5}$$

(1) is the objective function, which is to minimize makespan. (2) is the precedence constraint. (3) implies C_{max} as total time duration for all jobs while (4) is the disjunctive constraint which prevents a machine to perform two operations at the same time. The last constraint, (5) implies non-negativity start time.

3.2 Critical path

The purpose of finding critical path is to determine the total time for the operations to complete and to check the progress of the operations against the scheduled duration by allocating start and end time to all operations involved. The activities lie on the critical path are known as critical activities which indicates that those activities must start and end within the scheduled time. Any delay in critical path activities will cause a delay in total completion time of the activities.

3.3 Neighbourhood structure

It is a method that, by applying move to a set of neighbour solutions, to obtain a new neighbour solution. The type of neighbourhood structure used in this paper is neighbourhood structure 1 (N1) by Van Laarhoven et al. (1992). According to them, a move is made by changing the position of the adjacent jobs that operate on the same machine and involved in the critical path.

3.4 Move

Move is applied once the best solution is determined from the set of the neighbour solutions. This best solution should be the solution that is not included in tabu list. Given a situation where all the possible moves are tabu and no one satisfies the aspiration criterion, then the oldest move in the tabu list will be selected as the next move.

3.5 Tabu list

Tabu list prevents the solution from sticking in the local minima. With tabu list, the search will focus on the solutions that is not in the tabu list and the best current solution will be selected from this set of solution.

3.6 Aspiration criterion

Aspiration criterion is used to violate the tabu search. It is because tabu search sometimes is too powerful that it may skip the good solution. Thus, it is designed to prevent this kind of situation by cancelling the tabu status of a solution in tabu list if it is better than the current best-known solution. This means that aspiration criterion may allow the move which is tabu to be performed.

3.7 Termination criterion

Termination criterion is used to stop the search at certain point. In this paper, a fixed number of 1000 iterations are used to stop the search.

4. Implementation

This paper follows the tabu search algorithm by Geyik and Cedimoglu (2004) as below.

Step 1. Generate initial solution. Store the current makespan and current schedule as best makespan and best schedule.

Step 2. Select neighbour and move.

- Choose the neighbour from the critical path that is not tabu and move it as current new seed solution.
- Update tabu list.
- Store the selected neighbour as the new best solution provided if it gives a better solution.

Step 3. Repeat step 2 until a stopping criterion is achieved.

A flowchart for this algorithm is also shown in Figure 2. Tabu search requires initial solution for the search. The initial solution used here is disjunctive programming (DP). Before applying DP, the job order will be determined first using STPT and LTPT rules. Taken a sample data as shown in Table 2 from Pinedo (2008).

Table 2: A 4x3 JSSP Data

Jobs	Machine sequence	Processing time
1	1, 2, 3	$p_{11} = 10$, $p_{21} = 8$, $p_{31} = 4$
2	2, 1, 4, 3	$p_{22} = 8$, $p_{12} = 3$, $p_{42} = 7$, $p_{32} = 6$
3	1, 2, 4	$p_{13} = 4$, $p_{23} = 7$, $p_{43} = 3$

The total processing time for each job at all machines is calculated.

Job 1 = 10 + 8 + 4 = 22
Job 2 = 8 + 3 + 5 + 6 = 22
Job 3 = 4 + 7 + 3 = 14

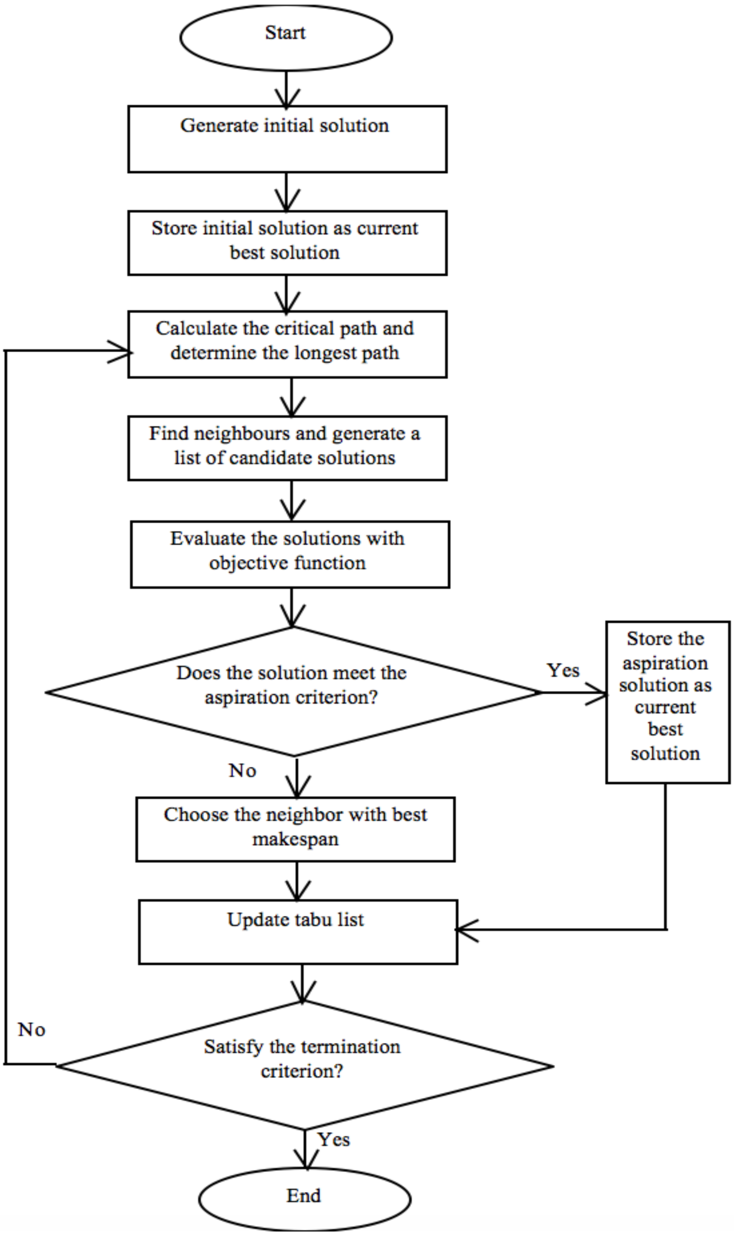

Figure 2: Flowchart of Tabu Search

By using STPT rule, the arrangement of jobs is $J_3 \rightarrow J_1 \rightarrow J_2$. If there exist same total processing time, choose arbitrarily. By using LTPT rule, the arrangement for the jobs is $J_1 \rightarrow J_2 \rightarrow J_3$. After the job order has been determined, set the programming as shown in Figures 3 and 4 using LINDO software.

The determination of these job orders are involved in constraint (4) of the disjunctive model. Based on Figures 3 and 4, the job order is set from line 19 to 26. Then the output of these programming are shown in figure 5 and 6. After the initial solution has been generated, it will be used as the current best solution to start the tabu search. Then, the determination of critical path will be considered. All the candidate solutions will be generated by the neighbourhood structure. If the solution reaches the objective function, it will be selected as tabu and listed in tabu list as current best solution. The tabu list will keep on updating when there is a new solution. The selection as mentioned here is known as move and will repeat until it reaches the termination criterion. Aspiration solution will be considered as well when the solution in the tabu list gives a better result.

```
MIN      CMAX
SUBJECT  TO
         2)    Y21 - Y11 >=    10
         3)    Y31 - Y21 >=    8
         4)    Y12 - Y22 >=    8
         5)    Y42 - Y12 >=    3
         6)    Y32 - Y42 >=    5
         7)    Y23 - Y13 >=    4
         8)    Y43 - Y23 >=    7
         9)    CMAX - Y11 >=    10
        10)    CMAX - Y21 >=    8
        11)    CMAX - Y31 >=    4
        12)    CMAX - Y22 >=    8
        13)    CMAX - Y12 >=    3
        14)    CMAX - Y42 >=    5
        15)    CMAX - Y32 >=    6
        16)    CMAX - Y13 >=    4
        17)    CMAX - Y23 >=    7
        18)    CMAX - Y43 >=    3
        19)    Y12 - Y11 >=    10
        20)    Y11 - Y13 >=    4
        21)    Y12 - Y13 >=    4
        22)    Y21 - Y23 >=    7
        23)    Y22 - Y21 >=    8
        24)    Y22 - Y23 >=    7
        25)    Y32 - Y31 >=    4
        26)    Y42 - Y43 >=    3
        27)    Y11 >=    0
        28)    Y21 >=    0
        29)    Y42 >=    0
        30)    Y32 >=    0
        31)    Y13 >=    0
        32)    Y23 >=    0
END
```

Figure 3: Program Code for STPT in LINDO

```
MIN      CMAX
SUBJECT  TO
         2)    Y21 - Y11 >=    10
         3)    Y31 - Y21 >=    8
         4)    Y12 - Y22 >=    8
         5)    Y42 - Y12 >=    3
         6)    Y32 - Y42 >=    5
         7)    Y23 - Y13 >=    4
         8)    Y43 - Y23 >=    7
         9)    CMAX - Y11 >=    10
        10)    CMAX - Y21 >=    8
        11)    CMAX - Y31 >=    4
        12)    CMAX - Y22 >=    8
        13)    CMAX - Y12 >=    3
        14)    CMAX - Y42 >=    5
        15)    CMAX - Y32 >=    6
        16)    CMAX - Y13 >=    4
        17)    CMAX - Y23 >=    7
        18)    CMAX - Y43 >=    3
        19)    Y12 - Y11 >=    10
        20)    Y13 - Y11 >=    10
        21)    Y13 - Y12 >=    3
        22)    Y23 - Y21 >=    8
        23)    Y22 - Y21 >=    8
        24)    Y23 - Y22 >=    8
        25)    Y32 - Y31 >=    4
        26)    Y42 - Y43 >=    3
        27)    Y11 >=    0
        28)    Y21 >=    0
        29)    Y42 >=    0
        30)    Y32 >=    0
        31)    Y13 >=    0
        32)    Y23 >=    0
END
```

Figure 4: Program Code for LTPT in LINDO

```
       OBJECTIVE FUNCTION VALUE

       1)       44.00000

VARIABLE         VALUE
    CMAX         44.000000
     Y21         14.000000
     Y11          4.000000
     Y31         22.000000
     Y12         30.000000
     Y22         22.000000
     Y42         33.000000
     Y32         38.000000
     Y23          7.000000
     Y13          0.000000
     Y43         30.000000
```

Figure 5: Initial makespan using STPT

```
       OBJECTIVE FUNCTION VALUE

       1)       54.00000

VARIABLE         VALUE
    CMAX         54.000000
     Y21         10.000000
     Y11          0.000000
     Y31         18.000000
     Y12         26.000000
     Y22         18.000000
     Y42         43.000000
     Y32         48.000000
     Y23         33.000000
     Y13         29.000000
     Y43         40.000000
```

Figure 6: Initial makespan using LTPT

5. Computational Results

Tabu search has been applied on some problem instances of different size which include 6 x 6 (FT06) by Fisher and Thompson (1963), 10 x 5 (LA05) and 20 x 5 (LA11) by Lawrence (1984) and 10 x 10 (ABZ6) by Adams et al. (1988). These are some famous benchmark problem instances that can be obtained from OR library.

Tabu search algorithm is coded in C++ language while for DP, the initial solution, the program is written in LINDO software. Comparison of tabu list length for FT06 is made between a list length of 4 (T4) and 10 (T10). Meanwhile, the remaining problem instances, LA05, LA11 and ABZ6 with larger size, the comparison is made between tabu list length of 12 (T12) and 16 (T16). The stopping criterion of a fix number of 1000 iterations is used. The effect of different dispatching rules, STPT and LTPT, used in conjunction with DP are evaluated. The results obtained is shown in Table 3.

Table 3: Tabu Search Solution Obtained using DP

Problem instances	**Dispatching rules**	**Makespan**	
		T4	**T10**
FT06	STPT	55	55
	LTPT	55	55
Problem instances	**Dispatching rules**	**Makespan**	
		T12	**T16**
LA05	STPT	593	593
	LTPT	593	593
LA11	STPT	1442	1210
	LTPT	1586	1489
ABZ6	STPT	948	965
	LTPT	1366	1366

From Table 3, by comparing the rules, all problem instances have a better result obtained using STPT rule except for both FT06 and LA05 which attained the same makespan for both STPT and LTPT rules. For LA11, it depicts makespan of 1442 at T12 and 1210 at T16 using STPT while results using LTPT are 1586 at T12 and 1489 at T16. For ABZ6, STPT indicates a better result of 948 at T12 and 965 at T16. Meanwhile, ABZ6 with LTPT gives a result of 1366 at both T12 and T16.

By comparing the tabu list length, the results depict in both FT06 and LA05 are 55 and 593 respectively. However, LA11 shows better result at T16 with 1210 using STPT rule and 1489 using LTPT rule. For ABZ6, it has a better result at T12 with 948 obtained using STPT and 1366 using LTPT.

The best makespan obtained is then compared with the benchmark values acquired by previous researchers in Table 4.

Table 4: Comparison between DP and Benchmark Values

Problem instances	**Best makespan (DP)**	**Benchmark values**
FT06	55	55
LA05	593	593
LA11	1210	1222
ABZ6	948	943

From Table 4, DP attained the same result as the benchmark values for FT06 and LA05. However, for LA11, DP acquired value better than the benchmark value. Meanwhile, DP shows a slightly poor performance with a value of 948 in ABZ6 which close to the benchmark values. Overall, from the perspective of the size of problem instances, DP performs well for both FT06 and LA05. Meanwhile, for LA11 with problem size of 10 x 5, DP obtains a value of 1210, which is better than benchmark values. This shows that DP can achieve a better solution for problem size of 10 x 5. However, DP shows a slightly poor result in problem size 10 x 10 (ABZ6) with a value of 948. This may due to the tabu list length since it requires some parameter tuning to get a good result. This may also caused by the problem size where DP may not suitable in solving JSSP of size 10 x 10.

6. Conclusions

Generally, this research studies the job shop scheduling problem (JSSP). Tabu search is chosen to be used in this research for solving the problem and DP with STPT and LTPT rules are used as initial solution for tabu search. The results show that DP with STPT rule offers the best solution. By comparing tabu list length, both FT06 and LA05 obtain same results for different tabu list length. For LA11, it performs well by 19.17% with tabu list length of 16 whereas for ABZ6, tabu list length of 12 is more suitable by 1.79%. To investigate the performance quality, the best tabu search solutions obtained using DP are then compared with the benchmark values from previous researchers. DP obtains a solution same as the benchmark values for FT06 and LA05 whereas for LA11, DP performs 0.99 % better compared to benchmark values. However, DP has a slightly error gap by 0.53% on ABZ6 with problem size of 10 x 10. Parameter tuning and problem size may be the factors that affect this result. Briefly, DP provides good result in the tabu search. However, DP gained a slightly reduced result on problem size of 10 x 10 (ABZ6). Since it is not possible for a method to fit on all the data measured, further study may test DP on different problem instances of the same size of 10 x 10 to further study the effect of the problem size on tabu search. More problem instances of different size which is not used in this study may also be tested in future research to evaluate the efficiency of DP on them.

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