Scheduling technology of satellites parallel final assembly based on Multi-island Genetic Algorithm

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Abstract. The satellite final assembly is a production process with thermal test workplace and mechanical test workplace as the core resources. The final assembly of each satellite shall guarantee the delivery date (the date of leaving factory) as well as the delivery of key time points. In this paper, a scheduling problem model is established aiming at minimizing the total delay penalty with the workplace resource as the main constraint for the multi-satellite parallel final assembly process. The problem is solved by designing Multi-island Genetic Algorithm. Finally, a case of satellite final assembly production is scheduled to arrange the corresponding assembly workplace for each process of each satellite. As a result, most of the satellites have little or no delay in key time points and delivery date. A practical scheduling plan is gotten.

1. Introduction
With the promotion and implementation of lunar exploration project, manned space project, Mars exploration, Internet constellation and other plans, the demand for satellite production is increasing year by year, and the current backward production management has been difficult to adapt to the expanding task requirements. In the process of satellite production, the final assembly process directly faces the pressure of the final delivery date, as well as the key time points (as shown in Figure 1). The improvement of production management means often plays a role of twice the result with half the effort.

The satellite final assembly is a production process with thermal test workplace and mechanical test workplace as the core resources. Multiple satellites are assembled in parallel. The mechanical test, thermal test and other processes of each satellite share core resources such as workplaces and test equipments. The delivery date (date of leaving factory) of each satellite is guaranteed, as well as the delivery of key time points. Therefore, the current multi-satellite assembly scheduling is faced with the problem that it is difficult to make detailed and long-term scheduling plan and reasonable allocation of core resources.
Scholars have carried out in-depth and extensive research on the production scheduling of multi-product under multi-constraint. Pezzella F[1], Bagheri A[2], Fernandez-Viagas[3] and Che A[4] designed optimization algorithms to minimize the maximum completion time or delay penalty, and complete the job scheduling by allocating the processing equipment, workers and other resources in the workshop. Lasserre[5] established an integrated optimization model of job shop production planning and scheduling, and used the multi-step transfer decomposition method to alternately solve the planning problem of given product processing sequence on each machine and the job shop scheduling problem of given plan, and finally obtained the feasible production planning and scheduling; For assembly shop scheduling, Reeja M K, and Rajendran C [6] put forward two concepts of OSD and ODD, and then put forward several corresponding scheduling rules for their respective optimization objectives. Dong [7] studied the integrated optimization model of production planning and scheduling of assembly line and proposed an improved particle swarm optimization algorithm to solve the model. Du [8] constructed a resource constrained multi-project scheduling model for aircraft tooling, aiming at the problem of resource competition among multiple projects of aircraft tooling complex products. The above research plays an important role in the actual production, but none of them can make a refined scheduling plan for the satellite final assembly process under the constraints of workplace resources. In order to minimize delay penalty, a Multi-island Genetic Algorithm is used to solve the problem, and a feasible scheduling plan is gotten.

2. Multi-satellite parallel final assembly scheduling problem description

The problem of multi-satellite parallel final assembly scheduling involves $n$ satellites $J_i (i = 1, 2, 3...n)$ and $s$ assembly workplaces $S_j (j = 1, 2, 3...s)$. Each satellite has a known delivery node, and its final assembly needs to go through the process shown in Figure 1. For satellite $J_i$, the $m$-th key time point in the process needs to be completed before the time point $K_{T_m}$. In the above process, each process has at least one workplace for assembly. The implementation of each process needs to be started on the basis that the workplace resources can be used are idle. The working time of a process is fixed.

The above problem is similar to the flexible job shop scheduling problem, but in this study, the necessary resources of each process are changed from equipment resources to workplace resources. In addition, due to the existence of key time points and delivery dates of satellites, the scheduling goal is also changed from minimizing maximum completion time of workpieces to minimizing total delay penalty of satellites (including the delay penalty of all satellite delivery dates and key time points).

3. Multi-satellite parallel assembly scheduling model

3.1. Symbolic Explanation
Parameters:
$J_i$: satellite, $i = 1, 2, 3 \cdots n$, $n$ is the number of satellites;

$S_l$: workplace, $l = 1, 2, 3 \cdots s$, $s$ is the number of workplaces;

$D_i$: delivery date of satellite $J_i$;

$K_{Tim}$: the $m$-th key time point of satellite $J_i$; $m = 1, 2, 3 \cdots K_i$, $K_i$ is the number of key time points of this satellite;

$P^c_i$: delay penalty coefficient of satellite $J_i$;

$O_{ij}$: the $j$-th operation of satellite $J_i$, $j = 1, 2, 3 \cdots G_i$, $G_i$ is the number of satellite $J_i$’s operations;

$X_{ijl} = \begin{cases} 
1, & \text{if operation } O_{ij} \text{ can be assembled on workplace } S_l \\
0, & \text{otherwise} 
\end{cases}$

$L$: a constant large enough;

Decision variables:

$S_{ij}$: start time of operation $O_{ij}$;

$E_{ij}$: end time of operation $O_{ij}$;

$AT_{ij}$: working hours of operation $O_{ij}$;

$F_i$: completion time of satellite $J_i$;

$F_{ij}$: completion time of the $j$-th key time point of satellite $J_i$;

$TP$: total delay penalty for all satellites

$ID_i = \begin{cases} 
1, & \text{if } F_i > D_i \\
0, & \text{otherwise} 
\end{cases}$

$ID_{Tim} = \begin{cases} 
1, & \text{if } F_{im} > K_{Tim} \\
0, & \text{otherwise} 
\end{cases}$

$U_{ijl} = \begin{cases} 
1, & \text{if operation } O_{ij} \text{ is assembled on workplace } S_l \\
0, & \text{otherwise} 
\end{cases}$

$B_{ijl} = \begin{cases} 
1, & \text{if operation } O_{ij} \text{ is assembled on workplace } S_l \text{ immediately after operation } O_{ij'} \\
0, & \text{otherwise} 
\end{cases}$

### 3.2. Model of Scheduling Goal

Equation (1) represents the scheduling goal of the problem, that is, minimizing the total delay penalty of all satellites.

$$\min : TP$$ (1)
Equation (2) describes the specific calculation method of the total delay penalty. \( \sum_{i=1}^{n} \left( F_i - D_i \right) \cdot ID_i \cdot pc_i \) is the penalty for delay in delivery of all satellites; \( \sum_{i=1}^{n} \left( F_{im} - K_{im} \right) \cdot ID_{im} \cdot pc_i \) indicates delay penalty for all key time points of all satellites.

\[
TP = \sum_{i=1}^{n} \left( F_i - D_i \right) \cdot ID_i \cdot pc_i + \sum_{i=1}^{n} \left( F_{im} - K_{im} \right) \cdot ID_{im} \cdot pc_i
\]  

(2)

Equation (3) is the specific calculation method of completion time \( F_i \) of satellite \( J \) in equation (2).

\[
F_i = \max \left( E_{ij} \right), \forall i, j
\]  

(3)

### 3.3. Model of Scheduling Constraints

Equation (4) - (5) is the operation constraint. Equation (4) describes the numerical relationship between the start time, end time and working hours of the operation. Equation (5) is the constraint of operation turnover, that is, an operation in the routing can be started only after the previous operation of the satellite is completed.

\[
E_{ij} = S_{ij} + AT_{ij}, \forall i, j
\]  

(4)

\[
S_{i(j+1)} \geq E_{ij}, \forall i, j
\]  

(5)

Equation (6) - (9) is the workplace constraint. Equation (6) indicates that there must be at least one workplace for any operation. Equation (7) and equation (8) indicate that there is only one workspace for any operation, which belongs to the optional workplace set. Equation (9) ensures that each workplace can only carry out one operation at most at the same time.

\[
\sum_{l=1}^{S} X_{ijl} > 0, \forall i, j
\]  

(6)

\[
X_{ijl} - U_{ijl} \geq 0, \forall i, j, l
\]  

(7)

\[
\sum_{l=1}^{S} U_{ijl} = 1, \forall i, j
\]  

(8)

\[
S_{ij} + \left( 1 - B_{ijl} \right) \cdot L \geq S_{ij} + AT_{ijl}, \forall i,i', j,j', l
\]  

(9)

### 4. Design of Multi-island Genetic Algorithm for satellite final assembly scheduling

Selection, crossover, mutation and other genetic operations in traditional Genetic Algorithm can only occur in a fixed population, and the optimal solution obtained is more likely to premature. Multi-island Genetic Algorithm can effectively suppress the occurrence of premature phenomenon. The operation flow of Multi-island Genetic Algorithm is shown in Figure 2.
When the Multi-island Genetic Algorithm runs, it first initializes the population and calculates the individual fitness. When the stop condition is met, it outputs a satisfactory solution. If the stop condition is not met, it splits the population and distributes the individuals to different "islands". The individuals on each "island" cross and mutate according to the rules and calculate the individual fitness. Then, the individuals who meet the migration conditions are transferred to other "islands", and the individuals who enter the next generation are selected. The above process is repeated until the stop conditions are met.

4.1. Coding Method Based on Operations
In this study, coding method based on operations is used. Chromosomes in the population represent the sequence of satellite final assembly operations. Figure 3 shows a chromosome code with four jobs. This code indicates that the first operation of job 1 is arranged first, then the first operation of job 3, the first operation of job 2 and the second operation of job 2, and the third operation of job 3 is arranged finally.

![Figure 3](image-url)
4.2. Crossing and Mutation of Chromosomes
In the calculation process of the algorithm, the chromosomes adopt the pox cross rule, that is, the genes in one offspring chromosome retain the position of one part of the operation coding of one parent chromosome, and the other part of the operation coding keeps the same sequence with that of the other parent chromosome. As shown in Figure 4. The method of mutation is reversing sequence of gene codes.

4.3. Fitness Function
Chromosome decoding is the process of arranging each operation, always arranging the operation to the earliest workplace can be assembled. Then the delay penalty is calculated according to the actual completion time of each operation. The algorithm takes the total delay penalty of multitasking as the fitness function, that is

\[
Fitness = TP = \sum_{i=1}^{K} (F_i - D_i) \cdot ID_i \cdot pc_i + \sum_{m=1}^{K} \sum_{i=1}^{F_m} (F_m - K_m) \cdot ID_m \cdot pc_i
\]  

(10)

4.4. Population Migration
After the algorithm is completed, the best part of the chromosomes in each "island" is selected to migrate to another random "island" according to the order of fitness function from small to large. In addition, most of the better chromosomes and a few of the worst chromosomes are selected to enter the next generation of calculation.

5. Case verification
The case for verification involves 8 satellites, each of which contains 7 operations. There are 3 assembly workplaces, 2 test workplaces, 1 Mechanical test workplace and 1 thermal test workplace in the final assembly hall. Among them, equipment installation, assembly before mechanical test and assembly before thermal test occupy assembly workplaces, electrical test and test before delivery occupy the test workplaces, mechanical test and thermal test occupy the required test workplace and equipment. The case of multi-satellite final assembly is shown in Table 1.
Table 1. Case of multi-satellite final assembly

| Operations                              | Satellites                  |
|-----------------------------------------|-----------------------------|
|                                         | XX-1 | XX-2 | XX-3 | XX-4 | XX-5 | XX-6 | XX-7 | XX-8 |
| 1. Equipment installation              | Working hours               | 90   | 90   | 85   | 85   | 85   | 180  | 90   | 150  |
|                                         | Required completion time    | 90   | 120  | 300  | 430  | 390  | 250  | 200  | 300  |
|                                         | Penalty coefficient         | 0.4  | 0.4  | 0.4  | 0.4  | 0.4  | 0.4  | 0.4  | 0.4  |
| 2. Electrical test                      | Working hours               | 60   | 50   | 45   | 45   | 45   | 90   | 40   | 30   |
|                                         | Required completion time    | /    | /    | /    | /    | /    | /    | /    | /    |
|                                         | Penalty coefficient         | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    |
| 3. Assembly before mechanical test      | Working hours               | 40   | 30   | 25   | 25   | 25   | 65   | 35   | 30   |
|                                         | Required completion time    | /    | /    | /    | /    | /    | /    | /    | /    |
|                                         | Penalty coefficient         | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    |
| 4. Mechanical test                      | Working hours               | 30   | 30   | 30   | 30   | 30   | 50   | 30   | 40   |
|                                         | Required completion time    | 230  | 230  | 410  | 540  | 500  | 480  | 330  | 450  |
|                                         | Penalty coefficient         | 0.2  | 0.2  | 0.2  | 0.2  | 0.2  | 0.2  | 0.2  | 0.2  |
| 5. Assembly before thermal test         | Working hours               | 40   | 30   | 30   | 30   | 30   | 55   | 35   | 30   |
|                                         | Required completion time    | /    | /    | /    | /    | /    | /    | /    | /    |
|                                         | Penalty coefficient         | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    |
| 6. Thermal test                         | Working hours               | 30   | 30   | 30   | 30   | 30   | 50   | 30   | 40   |
|                                         | Required completion time    | 320  | 320  | 500  | 630  | 590  | 600  | 430  | 550  |
|                                         | Penalty coefficient         | 0.3  | 0.3  | 0.3  | 0.3  | 0.3  | 0.3  | 0.3  | 0.3  |
| 7. Test before delivery                 | Working hours               | 20   | 10   | 10   | 10   | 10   | 30   | 20   | 10   |
|                                         | Required completion time (Delivery time) | 360  | 360  | 560  | 690  | 650  | 700  | 460  | 600  |
|                                         | Penalty coefficient         | 1    | 1    | 1    | 1    | 1    | 1    | 1    | 1    |

Multi-island Genetic Algorithm is used to solve the scheduling problem of the above case, with 150 iterations. After 20 calculations, the optimal scheduling result with the minimum fitness function (i.e. total delay penalty) is obtained. The convergence curve of the fitness function is shown in Figure 5.
Figure 5 convergence curve of the fitness function

It can be seen from the figure that the fitness function value converges from 766 to 142, and the convergence degree of genetic algorithm is good. The scheduling Gantt chart is shown in Figure 6.

Figure 6 Scheduling Gantt chart

In the above figure, S01~S03 are the assembly workplaces, S04~S05 are the test workplaces, S06 is the mechanical test workplace, and S07 is the thermal test workplaces. J01 ~ j08 represent the final assembly job of 8 satellites. According to the Gantt chart of production scheduling:

1. As the core resources, S06 and S07 are relatively intensive in production scheduling, and the workplaces S01~S03 are also relatively tense. However, S04 and S05 are idle for a long time due to short working hours and sufficient resources;

2. Because J01 and J02 have the same key time points and delivery time, the resources are tight, which leads to a long delay time, while other types of satellites can complete the final assembly before the delivery time;
(3) On the whole, most of the operations can be started in a short time after the completion of the previous operation, which has better operation connectivity. Moreover, most of the satellites have little or no delay in key time points or delivery time, and the scheduling results is good.

6. Conclusion
In the process of satellite final assembly, thermal test site and mechanical test site are the core resources of the production. At present, there are tight delivery time and key time points, so it is difficult to carry out practical production scheduling and optimal allocation of workplaces. In order to minimize the total delay penalty, this paper uses Multi-island Genetic Algorithm to solve the case. The main research work and conclusions are as follows:

(1) This paper describes and analyzes the current scheduling problem of multi-satellite parallel final assembly, and determines that the goal of the problem is to minimize the total delay penalty. And the model of multi-satellite parallel final assembly scheduling is established.

(2) For multi-satellite parallel final assembly, a Multi-island Genetic Algorithm is designed and applied to fine scheduling and optimal allocation of workplaces, and the case is solved. According to the production scheduling plan, most of the satellites can complete the final assembly before the delivery time.

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References
[1] Pezzella F, Morganti G, Cia G. “A genetic algorithm for the flexible job-shop scheduling problem.” Computers & Operations Research, 2008, 35(10): 3202-3212.
[2] Bagheri A, Zandieh M, Mahdavi I. “An artificial immune algorithm for “the flexible job-shop scheduling problem.” Future Generation Computer System, 2010, 26(4): 533-541.
[3] Fernandez-Viagas V, Perez-Gonzalez P, Framinan JM. “Efficiency of the solution representations for the hybrid flow shop scheduling problem with makespan objective.” Computers & Operations Research, 2019;109:77-88.
[4] Che A, Kats V, Levner E. “An efficient bicriteria algorithm for stable robotic flow shop scheduling.”. European Journal of Operational Research. 2017;260(3):964-971.
[5] Lasserre J B. “An integrated model for Job-Shop planning and scheduling”. Management Science, 1992, 38(9): 1201-1211
[6] Reja M K, Rajendran C. “Dispatching rules for scheduling in assembly jobshops-Part.” International Journal of Production Research, 2000, 38(9): 2051-2066
[7] Dong Q Y, Lu J S, Gui Y K. “Integrated optimization of production planning and scheduling in mixed model assembly line.” Procedia Engineering, 2012, 29(4): 3340-3347
[8] Du H, Lou P H, Ye W H. “Application of hybrid particle swarm optimization in resource constrained multi-project scheduling.” Journal of the Chinese Society of Mechanical Engineers, 2014, 35(5):371-379.