Research on Scheduling Problem of Discrete Manufacturing Workshop for Major Equipment in Complicated Environment

Chen Ruxiao¹, Lu Jianfeng *°, Zhang Hao¹ and Xia Luyao¹
¹College of Electronics and Information Engineering, Tongji University, Shanghai, 201800, China
*Corresponding author’s e-mail: lujianfeng@tongji.edu.cn

Abstract. This paper studies the scheduling problem of discrete equipment manufacturing workshops for major equipments in the context of commercial aircraft engine assembly workshops. At present, the manufacturing process of aircraft engines is still based on manual assembly, involving a large number of tooling parts, the workshop has large flow and long assembly period but limited labor. In this paper, the production scheduling process is optimized under the condition of multi-skilled human resources constraints. The mathematical programming model is established by abstracting the problem, and a heuristic algorithm based on multi-priority rules suitable for this problem is selected to solve the problem. Then, using Plant Simulation to establish a simulation model for the actual discrete assembly system, input different scheduling schemes and combine the logistics process for collaborative verification, and analyze the best scheduling results as a guide. The research shows that this method can effectively guide the workshop operation process, adapt to the constantly adjusted workshop layout, improve the resource utilization rate and assembly efficiency, and has a strong reference for practical application.

1. Introduction
The major equipment manufacturing industry in our country is large in scale, but its manufacturing process is mostly complex, requiring capital, technology, and labor intensive. There are also problems such as weak innovation ability, lack of key technologies, and insufficient basic supporting capacity. There is still a big gap compared with advanced countries, and there is an urgent need to develop smart manufacturing technologies to promote their industrial upgrading [1]. This paper selects the manufacturing of commercial aviation engines as the background for assembly workshop scheduling research, and strives to optimize the assembly environment and improve manufacturing efficiency.

In recent years, the problem of project scheduling has become a key issue for manufacturers to develop and improve their competitiveness. The manufacturing process of major equipment such as commercial aviation engines is large in scale, long in cycle, and highly sophisticated and complex. The assembly manufacturing process involves a wide variety of resources, and the assembly work is mainly done manually. Therefore, the decision-making of job scheduling and resource allocation determines the assembly manufacturing efficiency to some extent[2]. At present, many scholars at home and abroad have conducted in-depth research on this type of problem. Liao Guangrui et al[3] studied the project scheduling problem under the resource time window constraint; Bo Xin et al[4] studied the problem of multi-skilled workers in complex assembly systems.; Ren Yifei et al[5], considering that the job execution time varies depending on the skill level of the assigned key
resources; Fangjian Wei et al[6] proposed an improved greedy algorithm (IGA) based on the real aircraft assembly line and its characteristics, trying to solve the labor distribution problem (LAP), etc. The above research pays less attention to the application of the model in the actual complex assembly process. The heuristic algorithm based on multi-priority rules can obtain a solution to the search problem efficiently and quickly in the complex assembly system. Suitable for practical engineering applications.

Simulation is an effective way to make the theory more realistic at low cost. Zhang Yu[7] used eM-plant simulation software to simulate the three-level gate queuing system of the container to guide the control decision of the system; Tao Ningrong et al[8] based on the Plant Simulation simulation software, the shipyard segmentation transportation simulation model was established for simulation analysis and optimization; Li Wei et al[9] applied Plant Simulation to compare and analyze the scheme before and after the improvement of the welding frame balance of the bogie frame. Most of the above studies are based on the production process of batch or production line, or research on complex logistics processes, but this paper applies it to the aero-engine manufacturing workshop completely discretized in a single-piece small batch manufacturing mode, according to the actual assembly environment. The simulation model is built, and the solution algorithm is built into the model. The simulation scheduling scheme is applied to the actual production assembly process, and the complex logistics process is coordinated. The project utilization method and the logistics time are comprehensively analyzed to show the application of the project scheduling method. The actual effect has a stronger reference for the enterprise.

2. Formatting the title, authors and affiliations

2.1. Problem description

![AON Network diagram](image)

Figure 1. AON Network diagram

This paper will abstract the aeroengine assembly scheduling process with limited multi-skilled labor resources and describe the following: The job task set of the engine assembly process is \( J = \{1, 2, \ldots, n\} \), \( j \) is the job number, \( j \in J \), whose working time is \( t_j \), a fixed standard working time. The node-type (AON) directed network \( G = (V, E) \) represents a series of job tasks and their mutual relations, where \( V \) is the node, the arc set \( E \) represents the immediate relationship between the tasks, and \( P_j \) represents all the immediate work sets of job \( j \), the job must be started after its immediate work is completed, and the job process cannot be interrupted.

All tasks in the assembly process require a total of \( S \) skills, and all skills are provided by \( R \) kinds of renewable resources, where the skill set \( S = \{1, 2, \ldots, s\} \), \( s \) is the skill number, \( s \in S \), resource set \( R = \{1, 2, \ldots, R\} \), \( k \) is the resource number, \( k \in R \), assuming that there is no difference in the efficiency of labor resources with the same skill. The job-to-skill requirement can be represented by the job skill matrix \( JS = [r_{js}]_{|J| \times |S|} \). \( r_{js} \) indicates that the \( j \) job requires the \( s \) unit to have the \( s \) skills resource. The skills possessed by each resource are represented by the matrix \( RS = [\delta_{ks}]_{|R| \times |S|} \). \( \delta_{ks} = 1 \) indicates that the resource \( k \) has the skill \( S \), otherwise \( \delta_{ks} = 0 \). \( s_k \) indicates the number of skills owned by resource \( k \). \( r_g \) indicates the number of resources with skill \( s \). A job’s demand for any resource at a time cannot exceed the capacity of that resource, and at any moment, a resource can only use one skill on one job.
$ES_j$ and $EF_j$ respectively indicate the earliest start time and the earliest end time of job $j$, $LS_j$ and $LF_j$ respectively represent the latest start time and the latest end time of job $j$. $ST_j$ and $FT_j$ represent the start and end time of job $j$. $T$ is the total completion time of the engine assembly, $d \in D$, $D = \{1, 2, \cdots, d, \cdots, T\}$. The solution objective is to minimize the assembly time $T$ for various constraints.

Problem decision variable definition:
- $X_{ksj} = \begin{cases} 1 & \text{Resource } k \text{ uses skills } s \text{ to serve job } j \\ 0 & \text{otherwise} \end{cases}$
- $Y_{kdj} = \begin{cases} 1 & \text{Resource } k \text{ serving job } j \text{ at time } d \\ 0 & \text{otherwise} \end{cases}$
- $Z_{jd} = \begin{cases} 1 & \text{Job } j \text{ is working at time } d \\ 0 & \text{otherwise} \end{cases}$

2.2. Mathematical model
Through the analysis of the problem, the following integer programming type is constructed:

$$\text{Min } T;$$

s.t.

$$\sum_{j \in J} \sum_{k \in R} Y_{kdj} \leq R, \forall d \in D;$$

$$\sum_{s \in S} X_{ksj} \leq 1, \forall k \in R, \forall j \in J;$$

$$X_{ksj} \leq \delta_{ks}, \forall j \in J, \forall s \in S, \forall k \in K;$$

$$\sum_{l \in l} Y_{kdj} \leq 1, \forall k \in R, \forall d \in D;$$

$$\sum_{k \in R} X_{ksj} = r_{js}, \forall s \in S, \forall j \in J;$$

$$\sum_{d \in D} Z_{jd} = t_{j}, \forall j \in J;$$

$$t_{j}Z_{jd} - t_{j}Z_{jd+1} + \sum_{i=d+2}^{T} Z_{ji} \leq t_{j}, \forall j \in J, \forall d \in D;$$

$$d \times Z_{jd} \leq T, \forall d \in D, \forall j \in J;$$

$$t_{p}Z_{jd} \leq \sum_{i=1}^{P} Z_{pi}, \forall p \in P, \forall j \in J, \forall d \in D;$$

Equation (1) is the objective function, indicating that the goal of the research question is to minimize the assembly period; Equation (2) indicates that at any time, the total demand for resources for the job cannot exceed the supply of resources; Equation (3) indicates that each resource can only perform one job with one skill at most; Equation (4) means that a resource can only use this skill to perform an operation if it has a certain skill; Equation (5) indicates that the resource can only perform one job at a time; Equation (6) indicates that the number of people who use the skill $s$ to serve the job $j$ is exactly equal to the number of people who need the skill $s$; Equation (7) indicates that the job must be completed at the specified time, can not be extended; Equation (8) indicates that the process of job execution must be continuous, no interruption is allowed; Equation (9) indicates that the end time of each job cannot be later than the end time of the assembly item; Equation (10) indicates that the tight constraint relationship between the jobs needs to be satisfied; Equation (11) indicates that all decision variables are binary variables.
3. Model solving algorithm design

![Algorithm flowchart.](image)

Table 1. Job order priority rule

| Priority rule | Meaning                        | Numerical measurement |
|---------------|--------------------------------|------------------------|
| SPT           | Shortest processing cycle      | \( \min t_j \)        |
| LPT           | Longest processing cycle       | \( \max t_j \)        |
| SLK           | Minimum total time difference  | \( \min (TF_j = LS_j - ES_j) \) |
| EFT           | Earliest end time              | \( \min EF_j \)       |
| LFT           | Latest end time                | \( \min LF_j \)       |

*Supplementary rule: Minimum task number: \( \min j \).*

In this paper, a heuristic algorithm based on multi-priority rules is selected to solve the task scheduling plan under the minimum assembly period, and the random allocation method is selected for the resource allocation in the scheduling process. The multi-priority rule method uses the schedule generation mechanism multiple times, each time selecting different priority rules, and finally selecting the optimal solution as the final scheduling scheme. This paper selects the serial schedule generation mechanism and analyzes the priority rules for engine assembly.

The specific algorithm steps are as Figure 2:
• Step 1: Based on the AON network diagram, the key route method (CPM) analysis analyzes various time parameters of the job task, including: \(E_S_j, EF_j, LS_j, LF_j, TF_j\).
• Step 2: Initialize the scheduled job set \(S_g\), the candidate scheduled job set \(D_g\), the job set \(L_g\) that cannot be scheduled because one of the immediately preceding jobs has not scheduled the start time;
• Step 3: Select/replace the scheduling priority rule;
• Step 4: Select a task \(j^*\) from the candidate job set \(D_g\) according to the priority rule, insert the set \(S_g\), and update the set \(D_g, L_g\);
• Step 5: Allocate resource \(k\) and skills \(s\) for task \(j^*\), and update the resources available for subsequent allocation;
• Step 6: Under the premise of satisfying the tight relationship and resource constraints, arrange an early start time \(ST_j\) for the task \(j^*\) and calculate the end time \(FT_j\);
• Step 7: Execute the job \(j^*\). If \(D_g, L_g=\emptyset\), output the optimal assembly period \(T\) under this priority rule, generate a scheduling plan, and go to Step 8. Otherwise, go to Step 4.
• Step 8: \(n\) schedules have been derived based on \(n\) priority rules, and the optimal assembly period \(T\) is terminated and output, otherwise step 3 is performed.

4. Simulation to co-verify

In this paper, the Plant Simulation software is used to simulate the discrete assembly system, and the aeroengine assembly shop scheduling problem is studied. The simulation model of the assembly environment is shown in Figure 4. In addition to the assembly scheduling process, the simulation process of the entire system must be coordinated with the material distribution process. When the required parts fail to arrive on time or rework due to quality problems, the assembly process must wait or adjust. This is difficult to consider in the theoretical scheduling model.

In the simulation model, the scheduling algorithm under different priority rules is edited by the method, and the equipment such as the balancing machine is set to a certain failure rate, and the transportation vehicle calling rules and the transportation paths between different assembly stations
module in Plant Simulation can well simulate the role of human resources in the assembly process. Through the simulation test, the model outputs statistical analysis data after the simulation run.

Select a $J = 12$ process as the verification example, as shown in Figure 1, where job 1 is started as a virtual task with a job time of 0. Enter the resource skill matrix $RS$ and the job skill matrix $JS$ perform CPM analysis based on the AON network diagram, and calculate the latest start time $LS_j$, the latest end time $LF_j$, the earliest start time $ES_j$, earliest end time $EF_j$ and minimum total time difference $TF_j$ of each task. The following data is obtained through simulation analysis.

![Figure 4. Engine assembly workshop digital simulation](image)

Table 2. Aircraft engine assembly KPI

|       | Average station utilization | Completion Time | Average waiting time | Average personnel utilization | Logistics blocking rate |
|-------|-----------------------------|-----------------|----------------------|------------------------------|------------------------|
| SPT   | 76.3%                       | 28d             | 546m                 | 86%                          | 5.6%                   |
| LPT   | 70.8%                       | 33d             | 573m                 | 79.3%                        | 2.4%                   |
| SLK   | 71.4%                       | 30d             | 524m                 | 82.5%                        | 5.2%                   |
| EFT   | 70.4%                       | 32d             | 621m                 | 80.1%                        | 3.6%                   |
| LFT   | 73.6%                       | 30d             | 580m                 | 82.3%                        | 3.1%                   |

It can be seen from the above that the shortest assembly time is not necessarily the best solution, which may cause logistics congestion due to frequent transportation. Therefore, it is necessary to give certain weights to various simulation analysis indicators and comprehensively consider the effects. Thereby optimizing the overall assembly environment.

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**References**

[1] Jin Youye, Li Xingang, Zhao Yuxuan. Research on the development of major technical equipment manufacturing industry[J]. Agricultural Development and Equipment, 2016(5):44-44.

[2] Xin B, Li Y, Yu J, et al. A multi-factor revision based analysis of the personnel operational capacity of aircraft assembly lines[J]. The International Journal of Advanced Manufacturing Technology, 2015, 78(1-4):211-220.
[3] Liao Guangrui, Liu Zhenyuan, Bi Yang. Research on project scheduling under multi-skill resource time window constraints[C]. Proceedings of the 26th China Control and Decision Conference. 2014

[4] Xin B, Li Y, Yu J, et al. An adaptive BPSO algorithm for multi-skilled workers assignment problem in aircraft assembly lines [J]. Assembly Automation, 2015, 35(4): 317-328.

Thompson, J.N. (1984) Insect Diversity and the Trophic Structure of Communities. In: Ecological Entomology. New York. pp. 165-178.

[5] Ren Yifei, Lu Zhiqiang, Liu Xinyi, et al. Multi-skill resource constrained project scheduling considering skill level[J]. Journal of Zhejiang University (Engineering Science), 2017(5).

[6] Maghsoudlou H, Afshar-Nadjafi B, Niaki STA. A multi-objective invasive weeds optimization algorithm for solving multi-skill multi-mode resource constrained project Scheduling problem [J]. Computers & Chemical Engineering, 2016, 88:157-169.

[7] Zhang Yu. Simulation Research on the Gate System of Container Terminal Yard Based on eM-plant[J]. Logistics Engineering and Management, 2018.

[8] Tao Ningrong, Jiang Zuhua, Liu Jianfeng, et al. Simulation Modeling and Analysis of Shipyard Segment Transportation Problem Considering Multiple Flatbed Trucks[J]. Hebei Industrial Technology, 2017(06):5-10.

[9] Li Wei, Sun Li, Tong Xiaoying, et al. Balance Research and Simulation Analysis of Welding Production Line of Steering Frame[J]. Journal of Dalian Jiaotong University, 2017(04): 127-130.