Research on Scheduling Method of Ship Pipe Fittings Processing Workshop Based on Digital Twin

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Abstract: Aiming at the problems of insufficient real-time performance and lack of interaction in traditional pipe fitting processing workshop scheduling, this paper proposes a pipe fitting processing workshop scheduling method based on digital twins. It establishes a mathematical model with the objective function of minimizing the maximum completion time and designs an improved genetic algorithm to solve it. The algorithm selects individuals using roulette combined with elite retention strategy and improves the algorithm's optimization ability and convergence speed through dynamic crossover and mutation probability during iteration. Finally, the optimized scheduling scheme based on the digital twin obtained from the solution was compared with the existing pipe fittings production scheduling scheme of the enterprise, and the indicators reflecting the production level, such as the processing cycle and production waiting time of the optimized scheduling scheme, were significantly improved and optimized. At the same time, the number of equipment used was significantly reduced when the production tasks were determined.

1. Introduction

The shipbuilding industry is a modern comprehensive and strategic industry that provides technical equipment for water transportation, marine resource development and national defense construction. In order to accelerate the deep integration of the new generation of information and communication technology and advanced shipbuilding technology, most shipyards in my country have begun digital transformation to promote The intelligent level of ship assembly construction. Since shipbuilding is a typical discrete production and the shipyard has a large spatial scale, the shipbuilding cycle is relatively long, the process is complicated, the batch size is small, the number of non-standard parts of intermediate products is large, and the physical size varies greatly. Among them, pipe fittings processing is one of the most typical links in shipbuilding, and the quality of pipe fittings processing and production organization has a greater impact on shipbuilding. Therefore, this paper selects the pipe fittings processing workshop as a case study. By applying digital twin technology to improve its processing efficiency and optimize the production scheduling process of the workshop.

2. Literature Review

The flexible job shop scheduling problem (FJSP)[1] is a crucial issue in process planning and manufacturing, particularly for multi-variety and small-batch production in discrete manufacturing firms. The main objective of FJSP is to achieve the shortest completion time, and numerous scholars have conducted extensive research to address this problem. Several intelligent optimization methods have been proposed, such as Wang, Li, and Li's[2] multi-population collaborative genetic algorithm (MPCGA) and Yan et al.'s[3] three-layer redundant coding and correction decoding. The former optimizes the two sub-problems with the minimum maximum completion time, while the latter improves the genetic algorithm to address the constraints of limited transportation conditions. Meanwhile, Fan, Zhang, Liu, Shen, and Gao[4] study a flexible job shop scheduling problem with machine reconfiguration (FJSP-MR) to minimize the total weighted delay (TWT). Their numerical experiments show that the improved genetic algorithm is efficient in many cases for FJSP-MR, and

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the specially designed local search is an effective supplementary part of the basic genetic algorithm.

Despite the many methods proposed for FJSP, there is no algorithm that performs best for all FJSP problems. Therefore, selecting an intelligent optimization method with superior performance is necessary. Genetic algorithms (GAs) are a promising option because of their strong parallelism, adaptability, autonomous learning, and global search capabilities. While they can quickly find solutions for simple problems, they have limitations when addressing complex issues. Hence, improving GAs is crucial for practical problem-solving. Qais et al.[5] have emphasized the need to enhance GAs for this reason.

3. Construction of Mapping Interactive Model of Ship Pipe Fitting Processing Process and Production Scheduling

Realizing virtual-real mapping and real-time interaction through digital twins can realize the interactive fusion of workshop physical space and information space, which better adapts to the new needs of workshop scheduling. In actual production, there are many complicated factors in the pipe fittings processing workshop, and it is an important issue to schedule and optimize the pipe fittings processing process. To this end, a five-dimensional model of pipe fitting processing workshop scheduling based on digital twins was constructed, mainly including physical workshops and virtual workshops, workshop twin data, services and connections.

The specific content is arranged as follows: focusing on the twin data (DD) of the pipe fitting processing workshop, the production execution system of the physical pipe fitting processing workshop (PE) can obtain information related to scheduling in the production process in real time, and on this basis realize the pipe fitting production process Scheduling, such as equipment operation information, personnel on-duty status, processing task information and pipe fittings production status information, and finally, feed back to the corresponding virtual pipe fittings processing workshop (VE) through DD, VE is based on real-time perception data , combined with historical scheduling data, triggers an update and optimization process. At the same time, the updated simulation data is uploaded to DD, and the integrated twin data can drive a variety of workshop services, including production information statistics, workshop status monitoring, The online prediction of man-hours, the generation of real-time scheduling schemes, etc. are returned to PE through DD feedback for service output, forming a workshop scheduling process in which the virtual and the real are constantly iteratively evolving.

Based on the five-dimensional model, PE information is collected and sorted first, and then VE is constructed according to the workshop resource information to realize the mapping from entity to virtual, and real-time scheduling analysis is performed on the pipe fitting processing workshop, and the scheduling plan is passed between PE and VE through DD in real time Interactive iteration, with the help of the twin system of the pipe fittings processing workshop for data collection and feedback, the processing status and production information obtained in the VE are transmitted back to the PE, so as to realize the mapping from the virtual to the entity, achieve rapid information transmission and timely response, and improve production efficiency, continuity and initiative. At the same time, when the digital twin system of the pipe fittings processing workshop detects anomalies, it can be fed back to the digital twin system of the shipyard in time, so that the rest of the production workshops can adjust the production plan in time, improve the linkage and integrity of the workshops, and reduce the loss of resources and energy consumption.

In this five-dimensional scheduling model, on the one hand, various data required for production scheduling can be accurately obtained, including real-time data and historical data, which ensures the accuracy of the scheduling of the pipe fitting processing workshop and effectively meets the needs of the pipe fitting processing workshop due to changes in the pipe fitting process. Frequent and multi-piece customized production brings high production flexibility requirements, and can respond quickly, reduce waiting energy consumption, and reduce carbon emissions; on the other hand, it can analyze the workshop status and predict processing hours based on twin data The continuous interaction and feedback between them adjust the scheduling plan, respond to production disturbances in a timely manner, effectively monitor and feedback the automation equipment in the pipe fittings processing process in real time, improve the intelligent level of the workshop, and gradually realize integrated management.

Since the basis of the digital twin is to establish a virtual mapping of various physical objects in the actual production workshop, the foundation of establishing a virtual mapping is the information perception of the actual production workshop. Therefore, in order to realize the digital evolution of the pipe fittings processing workshop, a one-to-one mapping of virtual and real workshops is established to achieve a comprehensive perception of workshop information.

4. Problem description and model of FJSP

4.1. Problem description

The scheduling of pipe fitting workshop A can be defined as: n types of jobs (J = {J_1, J_2, J_3, ..., J_n}) are processed on m types of machines (m = {M_1, M_2, M_3, ..., M_m}). Each job has one or more operations, and the procedural order of operations within each job is predetermined. Each operation in any job can be performed by one of a predetermined set of capable machines. When operating on different machines, the processing time of the operation is not necessarily the same. FJSP will distribute each operation to the appropriate machine and determine the order in which operations are distributed on each machine to minimize the maximum time.

4.2. Model

The{C_1, C_2, C_3, ..., C_n}workpieces in the set of pipe fittings to be processed should be processed on{M_1, M_2, M_3, ..., M_m}machines in the machine set in the corresponding work area of the corresponding pipe fitting processing workshop. Each pipe fitting contains several processes, and each process has several machines to choose from.

According to the actual production situation, the following conditions need to be met:

(1) Each process of a workpiece can only be processed by one machine at the same time;

(2) The same machine can only process one workpiece at the same time;

(3) Once the process starts, it cannot be stopped;

(4) All workpiece processes have no priority configuration;

(5) The process of the same workpiece has sequence constraints, and there is no sequence constraint between different workpieces.

In order to facilitate the description and establishment of the model, the symbols are defined now:

Ω : collection of all artifacts

n : Total number of workpieces

m : Total number of machines

h_i : Total number of operations for operation i

i : Work No. Index $i = 1, 2, \cdots, n$

j : Process number index $j = 1, 2, \cdots, h_i$

k : machine serial number index $k = 1, 2, \cdots, m$

O_{ij} : the j process of workpiece i

H_{ij} : The set of optional processing machines for O_{ij}

O_{ijk} : O_{ij} processing on machine k

T_{ijk} : Processing time of O_{ij} on machine k

NJ : Sum of all workpiece operations

C_i : The finish time of job i

S_{ij} : Start time O_{ij}

C_{ij} : Completion time of O_{ij}

The objective function is to maximize the completion time and minimize:

$$\min\left\{\max C_j\right\}$$

The constraints of the model are as follows:

$$S_{ij} + X_{ijk} \times T_{ijk} \le C_{ij} \tag{1}$$

$$\mathrm{C}_{\mathrm{i}(j-1)} \le S_{ij} \tag{2}$$

$$C_{ij} \le C_{\max} \tag{3}$$

$$S_{ij} + T_{ijk} \le S_{xy} + W(1 - Y_{ijxyk}) \tag{4}$$

$$C_{i(j-1)} \le S_{ij} + W(1 - Y_{ijxyk}) \tag{5}$$

$$\sum_{k=1}^{m} X_{ijk} = 1 \tag{6}$$

$$S_{ij} \ge 0, C_{ij} \ge 0 \tag{7}$$

Formulas (1) and (2) indicate that the processes of the same workpiece must be processed according to the sequence of processes; Formula (3) indicates that the completion time of any process must not exceed the maximum completion time; Formulas (4) and (5) indicate that at any time Any machine can only process one process at the same time, where H is a very large number; Equation (6) indicates that a process can only be processed by one machine at a time; Equation (7) indicates the start time of any process and completion time are non-negative, and any workpiece can be processed at time 0.

5. Improved Genetic Algorithm

5.1. Encoding and decoding

Considering the characteristics of the problem (it is necessary to arrange the processing sequence of the process and select the corresponding machine for processing), parallel double-chain coding is adopted. The first layer is the coding layer based on the process, and the second layer is the coding layer based on machine selection. . As shown in Table 1, the number on the OS layer represents the workpiece number, and the number of occurrences is the process number of the current workpiece; the MS layer is arranged in the order of the workpiece processes, and 4 in this figure indicates that the first process of the workpiece No. 3 is in Processing on the No. 4 machine.

Table 1 Coding diagram.

OS	2	1	1	3	3
MS	2	5	3	4	1

5.2. Population initialization

The initial population is used to generate the first generation of offspring individuals, and the initial population is generated randomly.

5.3. Calculation of individual fitness value

Taking the minimization of the maximum completion time as the optimization goal, an elite retention strategy is adopted to avoid the optimal individual being destroyed due to the hybridization operation.

5.4. Selection operator

The roulette method is used to select individuals, and the calculation formula is as follows:

$$p(i) = \frac{f(i)}{sum(f)} \tag{8}$$

$$q(i) = \sum_{j=1}^{i} p(j) \qquad (j = 1, 2, 3, ..., i) \tag{9}$$

In the formula, $sum(f)$ represents the sum of individual fitness values, $P(i)$ represents the probability that individual i is selected, $q(i)$ is the cumulative probability of individual I, generate a random δ with values in the interval $[0,1]$,if $\delta \le q(i)$, then select the first individual;if , $q(i-1) < \delta \le q(i)$, then the i individual is selected.

5.5. Crossover and Mutation Operators

In this paper, the priority process crossover method (POX) is used to carry out the crossover operation. First, two base sequences J1 and J2 are randomly generated, and the genes in J1 contained in the paired parent individuals P1 and P2 are copied in situ to the offspring individuals In C2, C21, and the genes contained in are filled in the vacant genes of offspring individuals and in turn according to the original order, so as to obtain offspring individuals C1 and C2 after crossover.

Mutation is a small probability event, but it is beneficial to expand the diversity of the population. This project uses the exchange method (REM) for mutation operation, that is, randomly selects two gene bits containing different genes, and swaps the corresponding elements.

This paper adopts a dynamic self-adaptive crossover probability and mutation probability. On the one hand, a smaller or larger crossover and mutation probability is given to individuals according to their higher or lower status in the population. On the other hand, it has dynamic probability adjustment. At the beginning of the iteration, individuals cross and mutate with higher probability to expand the optimization range and avoid premature convergence of the algorithm. In the later stage of the iteration, the probability of crossover and mutation is reduced to reduce the excellent individuals obtained in the early stage from being crossed and mutated. The probability of destruction, while ensuring that the algorithm converges as soon as possible. The calculation formulas of the improved dynamic adaptive crossover probability and mutation probability are as follows:

$$u = \frac{\pi}{2(N-1)^v}(i-1)^v \tag{10}$$

$$P_c = \begin{cases} \cos(u)\dfrac{k_c(f_c - f_a)}{f_{\max} - f_a} & f_c > f_a \\ k_c & f_c \le f_a \end{cases} \tag{11}$$

$$P_m = \begin{cases} \cos(u)\dfrac{k_m(f_m - f_a)}{f_{\max} - f_a} & f_m > f_a \\ k_m & f_m \le f_a \end{cases} \tag{12}$$

In the formula, i is the current iteration number, N is the termination iteration number, the index v is the adjustment parameter, and the value is an integer in the interval $[1,5]$, P_c is the crossover probability, P_m is the mutation probability, and k_c and k_m are respectively the interval [0,1], f_m is the greater fitness value of the two crossover individuals, f_m is the fitness value of the mutant individual, f_a and $f_{\max}$ are the average fitness value and maximum fitness value of the current population, respectively.

6. Cases study

According to the characteristics of the pipe fittings to be processed in the pipe fittings processing workshop, it is proposed to form a part group by clustering according to the characteristics of the pipe fittings process, and then use the improved genetic algorithm to solve the target problem to obtain the final scheduling plan. This plan ensures the continuity of processing and improves Improve the production efficiency of the pipe fitting processing workshop. The relevant parameters of the pipe fittings group to be processed are sorted out as shown in Table 1, and the model is solved.

Table 1 Part group related parameters.

Optional machine	C_1	C_2	C_3	C_4	C_5	C_6	C_7
A_1(Open area)	/	/	/	/	/	/	M11
A_2(Open area)	/	M21, M22, M23	/	/	M21, M22, M23	M21, M22, M23	/
B_3(cutting area)	/	/	/	/	/	/	M31
B_4(cutting area)	M41, M42	/	M41, M42	/	/	M41, M42	/
B_5(cutting area)	/	M51	/	M51	M51	/	/
C_6(welding area)	M61, M62	/	/	M61, M62	M61, M62	M61, M62	/
C_7(welding area)	/	M71, M72	M71, M72	/	/	/	/
C_8(welding area)	/	/	/	/	/	/	M81
D_9(Hydraulic test area)	M91, M92, M93, M94, M95	M91, M92, M93, M94, M95	M91, M92, M93, M94, M95	M91, M92, M93, M94, M95	M91, M92, M93, M94, M95	M91, M92, M93, M94, M95	M91, M92, M93, M94, M95
D_{10}(Hydraulic test area)	/	/	/	/	/	/	M101
E_{11}(Paint treatment area)	/	/	/	M111	M111	/	/
F_{12}(bending area)	M121, M122	/	/	M121, M122	/	M121, M122	/

Using MATLABR2020a for calculation, the scheduling Gantt chart of the pipe fittings in the pallet is shown in Figure 2, and the maximum processing time of this batch of pipe fittings is 54.45h.

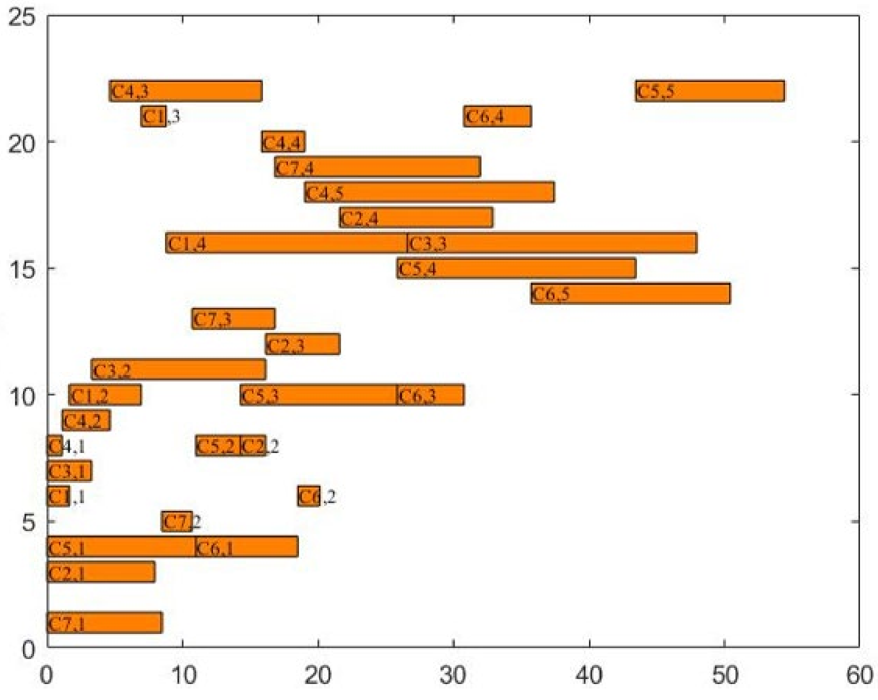

Figure 2 Scheduling plan Gantt chart.

7. Conclusion

Compared with the original production situation in the pipe fittings processing workshop of the shipyard (see Table 2), the optimized maximum processing time is 54.45 hours, while the maximum processing cycle of the traditional manufacturing method is 60 hours, and the processing cycle is shortened by 5.45 hours, which shortens the original 10.19% of the cycle. The optimized scheduling scheme reduces one processing equipment in the opening area.

Table 2 Comparison of the completion time of the workpiece before and after the optimization of the scheduling plan.

Optimization effect comparison	C_1	C_2	C_3	C_4	C_5	C_6	C_7
Traditional processing completion time /h	27.63	35.42	42.25	45.31	56.12	38.44	35.23
Optimized program processing time /h	26.6	26.25	37.5	37.44	54.45	33.75	31.96
Workpiece processing time reduction /h	1.03	9.17	4.75	7.87	1.67	4.69	3.27
Optimization percentage	3.73%	25.89%	11.2%	17.37%	2.98%	12.2%	9.28%

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