Multi-Objective Optimization of Prefabricated Component Transportation-Assembly Co-Scheduling Under Small Assembly Unit

Chunguang Chang[1][a], Shuqin Wang[1,*][b] and Yan Dong[2][c]
[1]*School of Management, Shenyang Jianzhu University, Shenyang 110168, China*
[2]*Finance Department, PetroChina Liaoning Marketing Company, Shenyang 110031, China*
*

Keywords: Prefabricated Components, Collaborative Scheduling, Multi-Skill, Multi-Objective, Hybrid Algorithm.

Abstract: Addressing the schedule and cost problems of prefabricated component (PC) assembly processes due to unreasonable distribution of PC, the transportation, assembly collaborative scheduling optimization model of PC was studied. The minimum completion time problem and the waiting cost problem in both transportation and assembly processes are analyzed, and the problem of large number of skilled workers in PC assembly process is also studied. A multi-skilled team of workers is used to carry out the assembly process, and a multi-objective optimization model of time-cost-workload equilibrium is set up in terms of the fairness of the multi-skilled group's work. Then a hybrid NSGA-II simulated annealing algorithm is designed to solve above model, and the PC transportation, assembly sequence and multi-skilled team allocation scheme are obtained, which verifies the effectiveness and practicality of the model and algorithm.

1 INTRODUCTION

Green, environment-friendly assembly building is in line with the national concept of sustainable development, however, there is big difference in the resource allocation of prefabricated component (PC) transportation, construction and other aspects of assembly building compared with traditional building type. Scholars at home and abroad have studied scheduling optimization model for PC transportation and assembly, Wang et al. (2023) developed a resource constrained scheduling model considering uncertain activity time of assembled buildings. Xiong et al. (2023) developed an optimization model for the PC loading combination scheme. Luo et al. (2023) studied transportation scheduling problem for assembly phase. Yin J et al. (2024) considered immediate lifting of PC on construction sites. Wang et al., (2018) integrated worker competence into prefabrication PC scheduling. Araz et al. (2019) also consider the multi-skilled nature of workers in off-site construction. Wang and Wu, (2021) consider the impact of the skill level of the multi-competent workers.

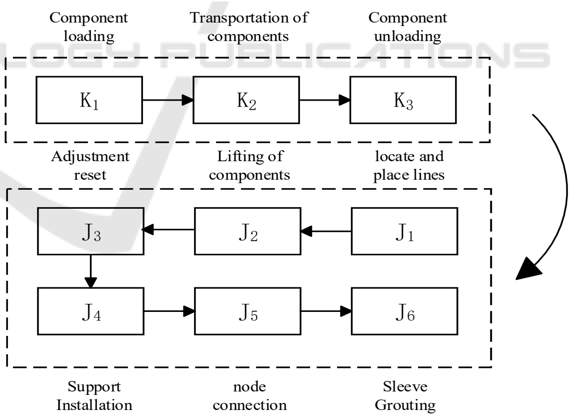


Figure 1: PC transportation-assembly scheduling flowchart.

[a] https://orcid.org/0000-0001-8379-7569
[b] https://orcid.org/0009-0007-8050-4637
[c] https://orcid.org/0009-0000-5342-2889

Chang, C., Wang, S., Dong and Y.
Multi-Objective Optimization of Prefabricated Component Transportation-Assembly Co-Scheduling Under Small Assembly Unit.
DOI: 10.5220/0013578800004671
In *Proceedings of the 7th International Conference on Environmental Science and Civil Engineering (ICESCE 2024)*, pages 130-135
ISBN: 978-989-758-764-1; ISSN: 3051-701X

2 DESCRIPTION OF THE PROBLEM

PC delivery will affect the duration and cost of the entire construction process, so the focus is on the overall transportation and assembly time and the waiting cost of unloading and lifting the PC according to the PC assembly process and lifting time requirements. Meanwhile, multi-skilled teams consisting of multi-skilled workers to fulfill the field assembly tasks and consider the fairness of workers' work. The PC transportation-assembly scheduling procedures are shown in Figure 1.

3 MATHEMATICAL MODELS

3.1 Symbol Definition

To describe the model clearly, common parameter and variable symbols and their definitions are given and listed in Table 1.

Table 1: Common Parameter and Variable Symbols and Definitions.

Symbol	Definitions	Symbol	Definitions
I	PC type number $I=1,2,\cdots M$, M is the total number of PC types	$P^{\mathrm{A}}_{(I,i),j}$	Actual operating time of procedure j for PC (I,i) during assembly
i	Single PC number, $i=1,2,\cdots N$, N is the total number of PC	$P^{\mathrm{A}_0}_{(I,i),j}$	Initial operating time of procedure j for PC (I,i) during assembly
k	Procedure number during transportation, $k=1,2,\cdots K$	$WT_{i,v,I}$	Waiting time for unloading vehicle v loaded with PC i of type I
j	Procedure number during assembly, $j=1,2,\cdots J$	$WL_{(I,i),j}$	Waiting time for lifting PC (I,i) at process j during assembly
v	Transportation vehicle number, $v=1,2,\cdots,V_I$, V_I is total number of vehicles loaded with PC type I	r	Multi-skilled shifts number, $r=1,2,\cdots,R$, R is team total number
B	Maximum load capacity of transport vehicle	$\tau_{j,r}$	Operating coefficient of a multi-skilled shifts r at process j during assembly
A_I	Weight of a single member of PC type I	$X_{i,v,I}$	Binary variable for type I PC i is delivered by vehicle v
$S^{\mathrm{TR}}_{i,v,k}$	Start time of procedure k for PC i loaded by vehicle v during transportation	$Y_{(I,i),j,r}$	Binary variable for procedure j for PC (I,i) is performed by a multi-skilled teams r during assembly
$S^{\mathrm{A}}_{(I,i),j}$	Start time of procedure j for PC (I,i) during assembly	$e_{j,r}$	Binary variable for the multi-skilled team r has the capability to complete the procedure j during assembly
$T^{\mathrm{TR}}_{i,v,k}$	Completion time of procedure k for PC i loaded by vehicle v during transportation	γ_1	Cost factor for waiting time for unloading
$T^{\mathrm{A}}_{(I,i),j}$	Completion time of procedure j for PC (I,i) during assembly	γ_2	Cost factor for waiting time for lifting of PC
$P^{\mathrm{TR}}_{i,v,k}$	Operating time of procedure k for PC i loaded by vehicle v during transportation		

3.2 Modeling

$$\min F = T^{\mathrm{A}}_{(M,N),J} \tag{1}$$

$$\min C = \gamma_1 \cdot \sum_{I=1}^{M}\sum_{v=1}^{V_I}\sum_{i=1}^{N} X_{i,v,I} \cdot WT_{i,v,I} + \gamma_2 \cdot \sum_{i=1}^{M}\sum_{i=1}^{N}\sum_{j=1}^{J} WL_{(I,i),j} \tag{2}$$

$$\min \sigma^2 = \frac{1}{R}\sum_{r=1}^{R}\left\{ \sum_{I=1}^{M}\sum_{i=1}^{N}\sum_{j=1}^{J} P^{\mathrm{A}}_{(I,i),j} \cdot Y_{(I,i),j,r} \cdot e_{j,r} - \frac{\sum_{I=1}^{M}\sum_{i=1}^{N}\sum_{j=1}^{J} P^{\mathrm{A}}_{(I,i),j}}{R} \right\}^2 \tag{3}$$

s.t.

$$T_{i,v,k}^{\mathrm{TR}} \geq S_{i,v,k}^{\mathrm{TR}} + P_{i,v,k}^{\mathrm{TR}} \quad i=1,2\cdots N,\ v=1,2,\cdots V_I,\ k=1,2,\cdots K \tag{4}$$

$$S_{i,v,k}^{\mathrm{TR}} \geq \max T_{i,v,k-1}^{\mathrm{TR}} \quad k=2,\ i=1,2,\cdots N,\ v=1,2,\cdots V_I \tag{5}$$

$$S_{i,v,k}^{\mathrm{TR}} \geq T_{i,v,k-1}^{\mathrm{TR}} + WT_{i,v,I} \quad k=3,\ i=1,2,\cdots N,\ v=1,2,\cdots V_I \tag{6}$$

$$WT_{i,v,I} = \max\left\{T_{i,v,k-1}^{\mathrm{TR}} - T_{i,v-1,k}^{\mathrm{TR}}, 0\right\} \quad k=3,\ i=1,2,\cdots N,\ v=1,2,\cdots V_I,\ I=1,2,\cdots M \tag{7}$$

$$S_{i,v,k}^{\mathrm{TR}} + P_{i,v,k}^{\mathrm{TR}} \leq \min S_{(I,i),j}^{\mathrm{A}} \quad k=3,\ j=2,\ i=1,2\cdots N,\ v=1,2,\cdots V_I,\ I=1,2,\cdots M \tag{8}$$

$$T_{(I,i),j}^{\mathrm{A}} \geq S_{(I,i),j}^{\mathrm{A}} + P_{(I,i),j}^{\mathrm{A}_0} \cdot \tau_{j,r} \cdot Y_{(I,i),j,r} \cdot e_{j,r} \quad I=1,2,\cdots M,\ i=1,2\cdots N,\ j=1,2\cdots J,\ r=1,2,\cdots R \tag{9}$$

$$S_{(I,i),j}^{\mathrm{A}} \geq \max\left\{T_{(I,i-1),j}^{\mathrm{A}}, T_{(I,i),j-1}^{\mathrm{A}}\right\} \quad I=1,2,\cdots M,\ i=1,2\cdots N,\ j=1,2\cdots J \tag{10}$$

$$WL_{(I,i),j} = \max\left\{S_{(I,i),j}^{\mathrm{A}} - T_{(I,i-1),j}^{\mathrm{A}}, 0\right\} \quad j=2,\ I=1,2,\cdots M,\ i=1,2\cdots N \tag{11}$$

$$Y_{(I,i),j,r} \leq e_{j,r} \quad I=1,2,\cdots M,\ i=1,2\cdots N,\ j=1,2\cdots J,\ r=1,2,\cdots R \tag{12}$$

$$X_{i,v,I} = 0 \text{ or } 1 \quad I=1,2,\cdots M,\ i=1,2\cdots N,\ v=1,2,\cdots V_I \tag{13}$$

$$Y_{(I,i),j,r} = 0 \text{ or } 1 \quad I=1,2,\cdots M,\ i=1,2\cdots N,\ j=1,2\cdots J \tag{14}$$

Equation (1) represents the minimum completion time required from transportation to assembly. (2) represents minimum waiting costs for unloading and lifting of PC, where, $V_I = \lceil N / \lfloor B / A_I \rfloor \rceil$. (3) represents the most balanced workload of the multi-skilled team. (4) to (6) indicate the operating time constraints for loading PC i at procedure k by vehicle v during transportation. (7) and (11) indicate the waiting time for unloading and lifting of PC, respectively. (8) indicates PC unloading delivery time constraints. (9) to (10) indicate the operating time constraints of PC (I,i) at procedure j. (12) represents the multi-skilled teams assigned during assembly has the capability to complete the task. (13) to (14) represent ranges of the variables.

4 ALGORITHM DESIGN

Above problem belongs to NP-hard problem, so NSGA-II algorithm by Deb et al. (2002) is chosen and mixed with simulated annealing algorithm. Its flow is as follows:

Step 1: Coding rules and creating initial populations, a two-segment chromosome coding structure is adopted, the first segment is the transportation phase, including vehicle allocation and PC scheduling coding based on the transportation process, and the second segment is the assembly phase, including multi-skilled shift assignment and PC scheduling coding based on the assembly process.

Step 2: Calculation of fitness value, in this paper, we solve for the fitness value based on the fitness function: $\text{fit} = \left[\text{F} \;\; \text{C} \;\; \sigma^2\right]$.

Step 3: Genetic operation, sorting and grading the individuals of the population according to the non-dominated sorting method, calculating the congestion distance between chromosomes of the same level, selecting the parent population using the binary tournament selection method, and then generating a new set of chromosomes by transferring some of the information of the parent to the next generation by means of crossover and mutation.

Step 4: Simulate the annealing operator search, accepting the optimal state in the region ensures a comprehensive search by means of probabilistic acceptance.

5 MODEL APPLICATION

5.1 Relevant Data Processing

A total of 8 PC exterior walls, 5 interior walls and 11 floor slabs are required in the area. The maximum load of the transportation trucks used is 16t, with a total of 5 trucks, and the cost of unloading and lifting waiting is 10 yuan/h and 60 yuan/h, respectively. Other relevant data are shown in Table 2, and multi-skilled team consisting of three multi-skilled workers, whose operating coefficients are shown in Table 3.

Table 2: Parameters related to PC.

Type of PC	PC number	unit weight (t)	unit of time /min			Initial operating time /min					
			K_1	K_2	K_3	J_1	J_2	J_3	J_4	J_5	J_6
A	1	3.2	4	50	5	12	18	8	12	12	5
	2		3	50	4	10	12	6	6	18	3
	3		3	50	4	10	12	6	6	18	3
	4		2	50	3	13	24	10	12	16	4
	5		4	50	5	12	18	8	12	12	5
	6		5	50	4	11	16	10	8	18	3
	7		3	50	3	12	18	8	12	12	4
	8		3	50	3	12	18	8	12	12	4
B	9	3	5	55	4	10	20	10	12	18	12
	10		3	55	6	12	18	12	16	24	10
	11		6	55	5	13	18	10	18	20	14
	12		4	55	6	10	18	8	16	22	12
	13		4	55	4	11	24	10	14	20	12
C	14	2.5	3	45	4	10	20	6	18	16	4
	15		2	45	3	12	18	4	16	14	4
	16		2	45	4	12	6	6	16	12	5
	17		3	45	3	11	12	6	18	14	6
	18		3	45	3	14	12	4	14	12	5
	19		2	45	3	12	18	4	16	14	4
	20		3	45	2	12	12	4	16	16	4
	21		2	45	2	14	16	6	18	16	2
	22		3	45	3	11	12	6	18	14	6
	23		3	45	4	10	20	6	18	16	4
	24		2	45	3	12	18	4	16	14	4

Table 3: Operational coefficients for multi-skilled teams.

Multi-skilled teams	Operating coefficient					
	J_1	J_2	J_3	J_4	J_5	J_6
1		0.88				
2	0.95		1.06	1.12		0.97
3			1.06	0.87	0.82	
4	0.95		0.83		0.94	1.11

5.2 Analysis of Results

To express simply, above data unit is converted to hour. The algorithm parameters are set as follows: population size 80, iteration 500, crossover probability 0.9, variance probability 0.1, annealing temperature 100, annealing rate 0.96. The results of the solution are shown in Figure 2. The Gantt chart for PC is shown in Figure 3, and the corresponding objective function values are: completion time 11.18 h, waiting cost 272.6 yuan, workload variance 33.18, and multi-skilled teams in a set of processes configured in the scheme 2-1-4-3-3-4. To verify the effectiveness of the hybrid algorithm, the result is compared with that by NSGA-II algorithm, and the convergence of the two algorithms is shown in Figure 4.

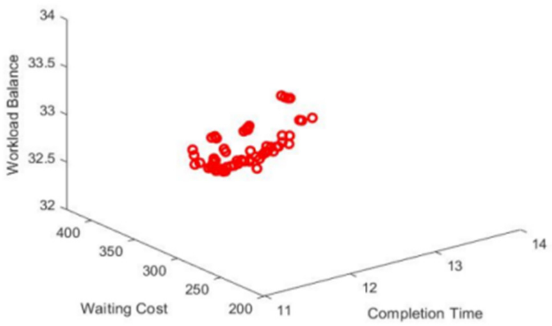


Figure 2: Three-dimensional Pareto frontier.

6 CONCLUSION

The PC co-scheduling model established in this paper ensures the immediacy of PC assembly at the construction site, provides methodological support for PC co-scheduling and staffing, which is an important direction for future construction enterprises to develop into knowledge-based enterprises, and verifies the effectiveness of the hybrid algorithm by comparing it with the NSGA-II algorithm.

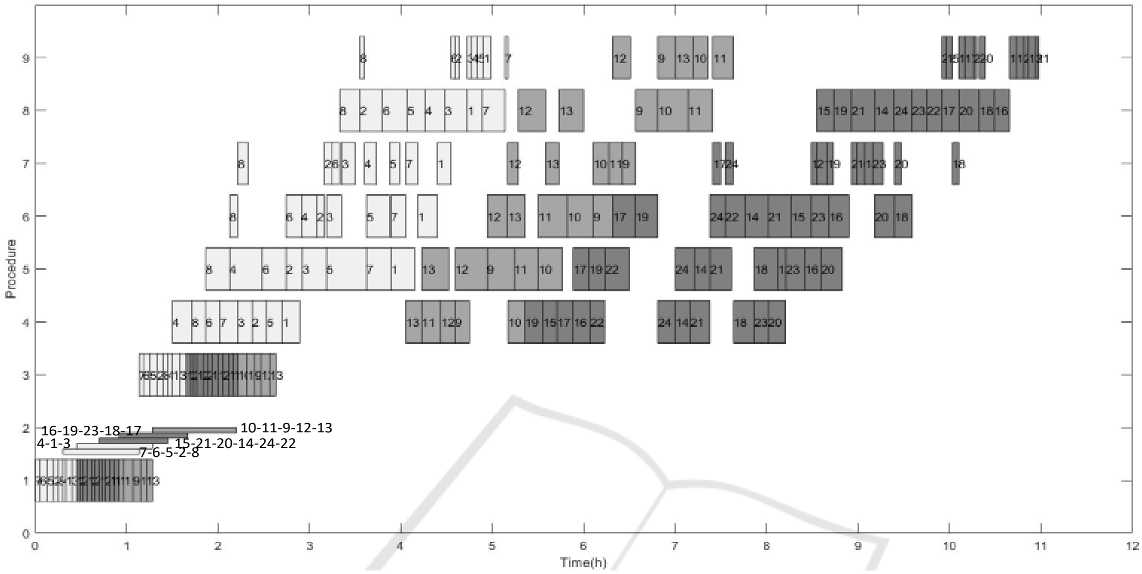
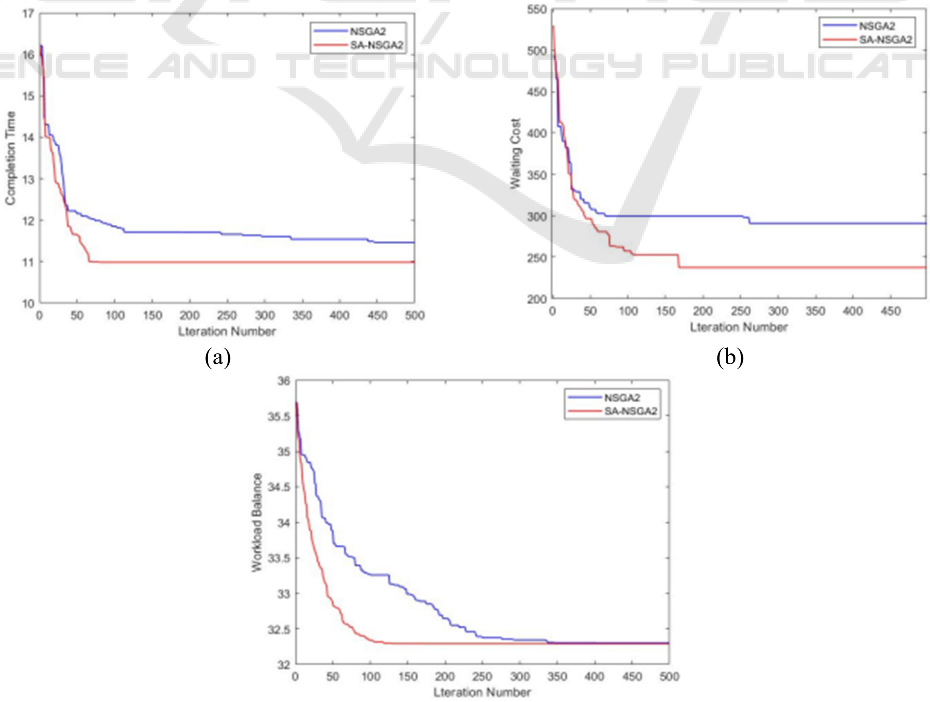


Figure 3: Gantt chart of the co-scheduling programme.



(a) (b)

(c)

Figure 4: Comparison of the convergence of the two algorithms.

ACKNOWLEDGEMENTS

This work is supported by Social Science Planning Fund project of Liaoning Province (L22BGL041).

REFERENCES

Wang, H., Gong, X., Li, Y. 2023. A Construction Scheduling Optimization of Prefabricated Buildings Based on Improved NSGA-II Algorithm. *Industrial Engineering Journal*, 26(2): 85

Xiong, F., Cao, J., Zhang, X. 2023. Integrated precast production scheduling and loading combination with considering time-varying characteristics of traffic congestion. *Computer Integrated Manufacturing System*, 29(8): 2761

Luo, Q, Deng, Q, Guo, X, et al. 2023. Modelling and optimization of distributed assembly hybrid flow shop scheduling problem with transportation resource scheduling. *Computers & Industrial Engineering*, 186: 109717

Yin, J, Huang, R, Sun, H, et al. 2024. Multi-objective optimization for coordinated production and transportation in prefabricated construction with on-site lifting requirements. *Computers & Industrial Engineering*, 189: 110017

Wang, Z., Hao, H., Gong, J. 2018. Modeling Worker Competence to Advance Precast Production Scheduling Optimization. *Journal of Construction Engineering and Management*, 144(11): 04018098.

Araz Nasirian, M., et al. 2019. Optimal Work Assignment to Multiskilled Resources in Prefabricated Construction. *Journal of Construction Engineering and Management*, 145(4).

Wang, Y., Wu, L. 2021. A Research on Multi-project Multi-skill Human Resource Scheduling Based on Improved NSGA-II. *Industrial Engineering Journal*, 24(3): 130

Deb, K., Pratap, A., Agarwal, S., et al. 2002. A fast and elitist multi objective genetic algorithm: NSGA-II. *Transactions on Evolutionary Computation*, 6(2): 182-197.