ATC-Based Production and Centralized Distribution Synchronized Decision-Making Optimization

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Abstract. To solve the problems of low solution fit, mutual constraints of solutions in the production and centralized distribution segments in complex production systems and the difficulty of global optimization in a single segment, this paper introduces the analytical target cascading (ATC) method, constructs a multi-objective hierarchical optimization model consisting of time and cost indicators, and designs a solution strategy combining the NSGA-II and ATC.

Keywords: ATC · synchronized decision-making · NSGA-II

1 Introduction

For production systems, collaborative optimization of all components is required to improve overall system performance. In a complex production system where there is a centralized distribution chain, the scheduling plan of the production chain on the one hand affects the production efficiency of the whole system as well as the planning of other chains such as distribution and storage, on the other hand, the centralized distribution solution affects product inventory levels and delay rates, so it was necessary to find a way to optimize both production and pooling plans. Wang [1] et al. proposed management measures for specific outfitting parts supply hub from the perspective of the supply hub. Regarding production scheduling, most of the existing studies focus on single shop scheduling aspects, such as the flexible job shop scheduling problem [2] and the hybrid flow shop optimization problem [3]. However, for the whole production system, scheduling optimization of a single link has limited effect on the improvement of the whole system, and studies have been conducted to collaboratively optimize multiple links in the production system to improve the efficiency of the production system, such as the collaborative optimization of the production and centralized distribution links [4, 5]. In most production processes, the core of an efficient production system is the synergistic operation of the production and distribution chain [6]. The ATC was proposed by Kim [7] et al. for solving objective optimization problems of complex systems and is suitable for solving distributed decision problems with hierarchical structure. In this paper, the dynamic linkage between production and centralized distribution links in the

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enterprise production system is studied, and the hierarchical optimization method combining NSGA-II and ATC is proposed by analyzing the coupling relationship between production and centralized distribution links.

2 Problem Description and Modeling

The research involves the processes of processing and production of workpieces on the shop floor, temporary storage before flush set, sending to the supply hub after flush set, and storage at the supply hub. The specific parameter symbols are shown in Table 1.

2.1 Top-Level Mathematical Model

The system-level optimization of each objective is carried out mainly from the perspective of storage time and cost of the centralized distribution chain to narrow the gap between it and the system optimization objective. The pallet delivery time, pallet completion time, pallet completion time of each workpiece in the pallet, as well as the shop floor temporary storage time cost and storage time cost are coordinated and optimized at the system level by considering the storage capacity constraint at each moment in the consolidation center, using the pallet completion time $t^{l}_{off,i}$ and the total shop floor processing cost TC_p as the contact and response variables, respectively.

$$min(\left\| TC - TC^0 \right\| + \varepsilon^R) \tag{1}$$

st.

$$\sum_{i=1}^{n} (t^{l}_{off,i} - t^{l0}_{off,i}) + (TC_p - TC_p^0) \leq \varepsilon^R \tag{2}$$

$$\sum_{i=1}^{n} S_{it} \leq V_t, \quad \forall t \tag{3}$$

$$TC = TC_{sto} + TC_p + TC_{del} \tag{4}$$

$$TC_{sto} = C_{sto} \cdot \sum_{i=1}^{n} (DL_i - t_{in,i}), \, t_{in,i} < DL_i \tag{5}$$

$$t_{in,i} = t^{l0}_{off,i} \tag{6}$$

$$TC_{del} = C_{del} \cdot \sum_{i=1}^{n} Del_i \tag{7}$$

$$Del_i = t_{in,i} - DL_i, \, t_{in,i} > DL_i \tag{8}$$

Table 1. Parameter symbols and meanings

Symbols	Meaning	Symbols	Meaning
i	Pallet number, $i = 1, 2, \cdots, n$	$\mathbf{Q}_i$	Collection of workpieces in pallet i
j	Machine number, $j = 1, 2, \cdots, MJ$	$\mathbf{M_k}$	Collection of available processing machines for process k
k, k'	Operation number, $k, k' = 1, 2, \cdots, k_{pi}$	F_{kpi}	Completion time of process k for workpiece p in pallet i
p, p'	Workpiece number, $p, p' \in \mathbf{Q}_i$	$t^e_{off,i}$	Completion time of the first workpiece in pallet i
n	Number of pallets	$t^l_{off,i}$	Completion time of the last workpiece in pallet i
MJ	Number of machines in the workshop	T_{kpij}	Processing time on shop machine j for process k of workpiece p in pallet i
k_{pi}	Number of processes for workpiece p in pallet i	V_t	Storage capacity of the supply hub at time t
L	A large enough positive number	C_p	Processing cost per unit time in processing plant
C_f	Fixed processing costs in processing plant	C_{buf}	Caching cost per unit time in the workshop
C_{sto}	Storage cost per unit time in supply hub	C_{del}	Pallet extension unit time cost
$t_{in,i}$	The time when the workpiece in pallet i enters the concentration center after flush set	TC_p	Total production cost of processing plant
TC_{buf}	Caching costs in the processing plant	TC_{sto}	Supply hub storage costs
TC_{del}	Pallet Trailing Costs	Del_i	Extension time for pallet i
DL_i	The delivery period of pallet i		
X_{kpij}	Workshop level decision variable, equal to 1 means that process k of workpiece p in pallet i is processed on workshop machine j, and vice versa is 0		
$Z_{kpk'p'j}$	Shop floor decision variable equal to 1 means that process k of workpiece p is processed before process k' of workpiece p' on shop floor machine j, and vice versa is 0		
S_{it}	A decision variable at the hub level of 1 means that at time t pallet i is stored in the hub and consumes storage resources, and vice versa is 0		

Where: Eq. (1) represents the objective of minimizing the TC and the TC^0 as well as minimizing the ε^R. Equation (2) is a necessary condition for the ATC coordination mechanism. Equation (3) is the storage resource constraint of the supply hub. Equation (4) represents the total cost of the centralized distribution and production chain, including storage costs, processing costs, and extension costs. Equation (5) and Eq. (7) for storage cost and deferred cost calculation, respectively. Equation (6) indicates that the pallet entry time into the supply hub is equal to the time after pallet flush, ignoring the transport time. Equation (8) indicates how the pallet extension time is calculated.

2.2 The Underlying Mathematical Model

The bottom model schedules the workpieces in each pallet in the shop, including developing a reasonable workpiece processing sequence and assigning reasonable processing machines to the processes, so that the difference between the top and bottom linkage variables and the response variables is minimized.

$$min \sum_{i=1}^{n} \left\| t^{l}_{off,i} - t^{0}_{off,i} \right\| + \left\| TC_p - TC^{0}_{p} \right\| \tag{9}$$

st.

$$\sum_{j \in \mathbf{M_k}} X_{kpij} = 1, \quad \forall k, p, i \tag{10}$$

$$F_{1pi} \geq \sum_{j \in \mathbf{M_k}} T_{1pij} \cdot X_{1pij}, \quad \forall p, i \tag{11}$$

$$\begin{gathered} F_{(k+1)pi} \geq F_{kpi} + \sum_{j \in \mathbf{M_k}} \left(T_{(k+1)pij} \cdot X_{(k+1)pij} \right) \\ \forall p, i, k, k \neq k_{pi} \end{gathered} \tag{12}$$

$$\begin{aligned} & Z_{kpk'p'j} + Z_{k'p'kpj} = X_{kpij} \cdot X_{k'p'ij} \\ & \forall p, p', k, k', j \in (\mathbf{M_k} \cap \mathbf{M_{k'}}), p \neq p', k \neq k' \end{aligned} \tag{13}$$

$$t^{e}_{off,i} = min(F_{kpi}), \quad \forall i, k = k_{pi}, p \in \mathbf{Q}_i \tag{14}$$

$$t^{l}_{off,i} = max(F_{kpi}), \quad \forall i, k, p \in \mathbf{Q}_i \tag{15}$$

$$TC_p = C_f + C_p \cdot \sum_{i=1}^{n} \sum_{p \in \mathbf{Q}_i} \sum_{k=2}^{k_{pi}} \left(F_{kpi} - F_{(k-1)pi} \right) + TC_{buf} \tag{16}$$

$$TC_{buf} = C_{buf} \cdot \sum_{i=1}^{n} (t_{off,i}^{l} - t_{off,i}^{e}) \tag{17}$$

Where: Eq. (9) is the underlying objective function. Equation (10) indicates that the process of the workpiece can only be processed on one machine. Equation (11) and Eq. (12) ensure that the next process can start only after the completion of the previous one. Equation (13) restricts the sequence of processes for the same or different workpieces on the same machine. Equation (14) represents the completion time of the first workpiece in the pallet. Equation (15) represents the flush time of the pallet. Equation (16) represents the total processing cost of the production chain. and Eq. (17) represents the workshop temporary storage cost.

3 Practical Case Study

In this section, a ship's tube processing workshop is selected to carry out the simulation solution for the production and distribution link. Figure 1 shows the working hours and process information of the pipe fittings in the pallets. The storage resources consumed by each pallet are known, and Table 2 shows the storage capacity of the assembly center at different times and related cost information.

3.1 Analysis of Results

The solution process of ATC is an iterative convergence process at each level, first solving the top-level model, obtaining the contact and response variables and passing them to the bottom-level. For the bottom-level model, NSGA-II is used to solve the model with completion time and staging time as the target. It is determined whether the solution in the non-dominated solution set satisfies the requirements, and if not, the iteration continues.

The results of the linked decision optimization are compared with the independent decision optimization results, and the results are shown in Fig. 2. From the comparison of the two solutions, it can be seen that the linkage decision solution can effectively control the processing cost and temporary storage cost while significantly reducing the delay cost and storage cost, and the final total cost can be reduced by 34.2% compared with the independent decision optimization, which verifies the effectiveness of the method of this paper.

Table 2. Supply hub storage capacity

Time	[0,30]	[30,40]	[40,50]		[50,60]
Storage capacity	2ε	3ε	5ε		7ε
Cost Category	Fixed processing costs	Unit processing cost	Temporary storage cost	Storage costs	Delayed costs
Cost (RMB)	400	100	50	50	70

Pipe No.	Process Information Optional equipment number (processing time)							Batch	Pallets	Storage consumption	Centralized distribution time
	Cutting	Bend tube	Calibrated tubes	Welding	Polishing	Water pressure test	Surface treatment				
J1	1 (0.05)	4 (0.15)		9/10 (0.1/0.08)	13/14 (0.08/0.06)	15/16 (0.1/0.08)	18 (0.16)	35	A	2ε	60
J2	2/3 (0.06/0.05)		7/8 (0.06/0.05)	9/10 (0.1/0.3)	13/14 (0.1/0.1)	15/16 (0.2/0.1)		50			
J3	1 (0.04)	4 (0.15)	7/8 (0.09/0.08)	11 (0.1)	13/14 (0.07/0.08)	15/16 (0.06/0.1)		60			
J4	1 (0.08)			11 (0.2)	13/14 (0.05/0.06)	17 (0.7)		40	B	3ε	40
J5	2/3 (0.04/0.04)		7 (0.05)	12 (0.1)	13/14 (0.05/0.04)	17 (0.15)	18 (0.2)	35			
J6	2/3 (0.05/0.06)	5/6 (0.2/0.3)		11/12 (0.1/0.1)	13/14 (0.08/0.1)	15/16 (0.06/0.08)		25			
J7	1 (0.06)		8 (0.06)	9/10 (0.15/0.1)	13/14 (0.08/0.08)	15/16 (0.05/0.05)		50	C	2ε	20
J8	1 (0.05)		7 (0.05)	9 (0.1)	13/14 (0.03/0.04)	15/16 (0.06/0.07)		35			
J9	2/3 (0.03/0.04)	5/6 (0.15/0.08)		9/10 (0.1/0.2)	13/14 (0.04/0.04)	17 (0.2)	18 (0.1)	40	D	4ε	50
J10	2/3 (0.05/0.05)		8 (0.06)	11/12 (0.08/0.1)	13/14 (0.03/0.04)	17 (0.1)		35			
J11	2/3 (0.07/0.06)	5/6 (0.2/0.1)		11/12 (0.1/0.15)	13/14 (0.05/0.05)	15/16 (0.1/0.15)	18 (0.2)	30			
J12	1 (0.08)		8 (0.05)	11 (0.15)	13/14 (0.05/0.06)	15/16 (0.08/0.15)		45			
J13	1 (0.05)	4 (0.15)		9/10 (0.1/0.08)	13/14 (0.08/0.06)	15/16 (0.1/0.08)	18 (0.16)	35	E	ε	50
J14	1 (0.08)			11 (0.2)	13/14 (0.05/0.06)	17 (0.1)		40			
J15	2/3 (0.04/0.04)		7 (0.05)	12 (0.1)	13/14 (0.05/0.04)	17 (0.15)	18 (0.2)	35	F	2ε	45
J16	1 (0.05)		7 (0.05)	9 (0.1)	13/14 (0.03/0.04)	15/16 (0.06/0.07)		35			
J17	2/3 (0.03/0.04)	5/6 (0.15/0.08)		9/10 (0.1/0.2)	13/14 (0.04/0.04)	17 (0.2)	18 (0.1)	40			
J18	2/3 (0.05/0.05)		8 (0.06)	11/12 (0.08/0.1)	13/14 (0.03/0.04)	17 (0.1)		35	G	3ε	70
J19	1 (0.08)		8 (0.05)	11 (0.15)	13/14 (0.05/0.06)	15/16 (0.08/0.15)		45			
J20	2/3 (0.07/0.06)	5/6 (0.2/0.1)		11/12 (0.1/0.15)	13/14 (0.05/0.05)	15/16 (0.1/0.15)	18 (0.2)	30			
J21	2/3 (0.05/0.06)	5/6 (0.2/0.3)		11/12 (0.1/0.1)	13/14 (0.08/0.1)	15/16 (0.06/0.08)		25			

Fig. 1. Information on pipe processing

Pallet	A	B	C	D	E	F	G
Independent decision making	46.6	36.8	49.1	59.15	56.8	51.55	48.65
Connected decision making	58.7	38.4	22.7	55.05	52.3	42.3	41.9

Related Costs	Production costs	Temporary storage cost	Delayed costs	Storage costs	Total cost
Independent decision making	6315	6915	3612	1897.5	18739.5
Independent decision making	6270	3672.5	703.5	1685	12331

Fig. 2. Pallet flush time and cost information

4 Conclusion

This paper establishes a mathematical model of the production and centralized distribution chain based on the ATC method and designs a solution method to coordinate the resource allocation, operation and decision parameters of the production and distribution chain. The results show that the linkage optimization method proposed in this paper can effectively reduce the cost consumption of the production system and realize the synergistic operation of production and distribution from the system level.

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