



基于强化学习驱动NSGA-II算法的 多目标混合柔性流水车间调度研究

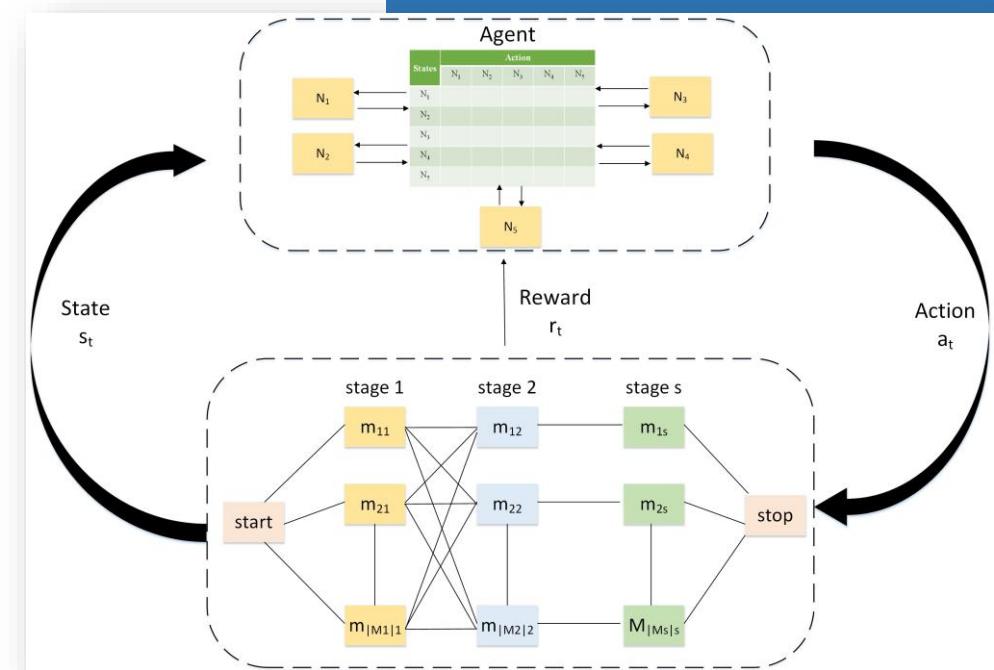
Muti-objective energy-efficient hybrid flow shop scheduling using Q-learning and VNS driven NSGA-II

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2023年3月26日





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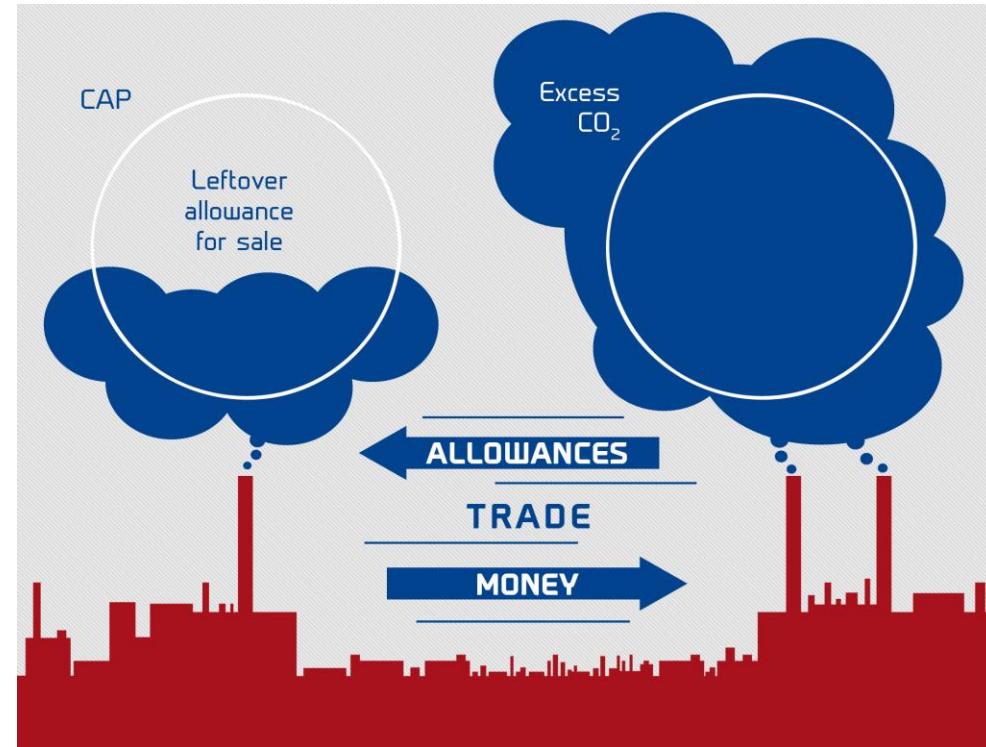
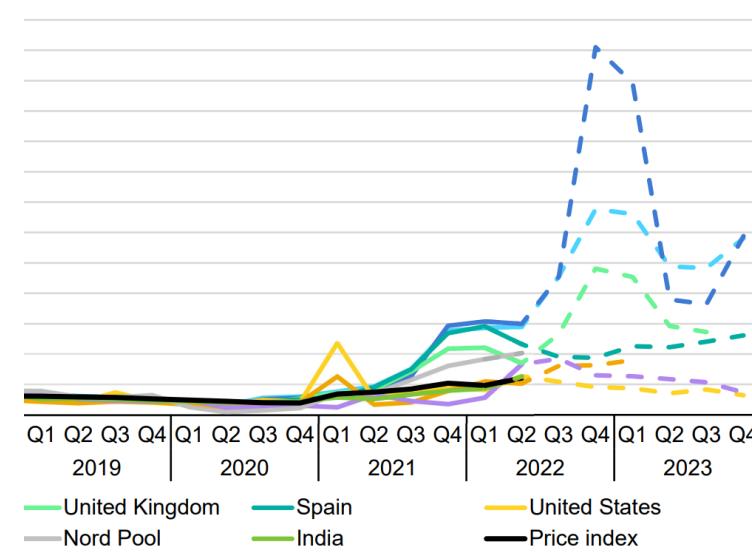
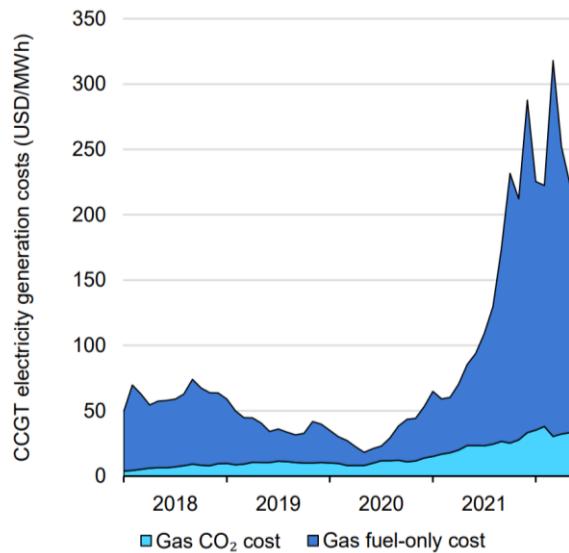
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第一部分 | 论文引言

1. 论文引言——研究背景

国际能源危机

在过去的50年里，能源消耗增加了**300%**，到2040年，全球能源需求将增长**37%**，人类面临能源困境^[1]



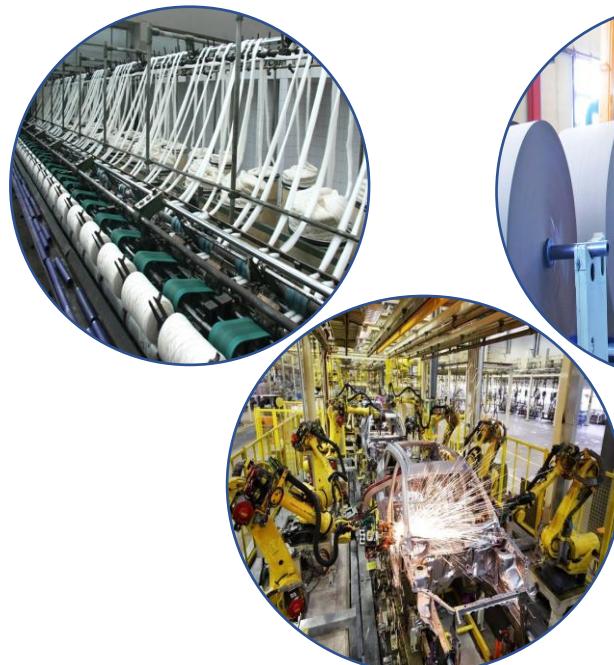
- ✓ 新冠疫情和地区冲突加剧了能源紧缺危机，世界能源价格持续上升；
- ✓ **工业生产**消耗了**近47%**的能源，因此**车间节能调度**成为节能减排的重要途径。

[1] Che, A., X. Wu, J. Peng, and P. Yan. 2017. "Energy-efficient Bi-objective Single-machine Scheduling with Power-down Mechanism." Computers & Operations Research 85: 172–183. doi:10.1016/j.cor.2017.04.004.

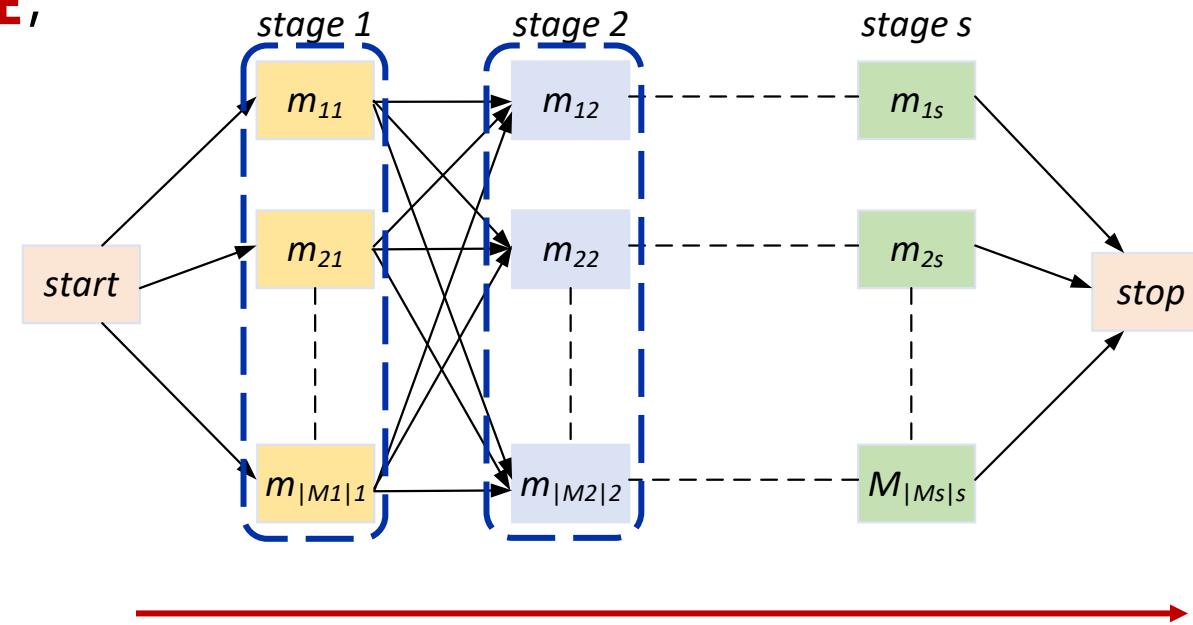
1. 论文引言——研究背景

混合流水车间 (Hybrid flow shop, HFS)

HFS是一种广泛应用于制造业、纺织业和电子业的生产系统，优点是具有**柔性**，使用于**多品种、小批量生产**^[2]。



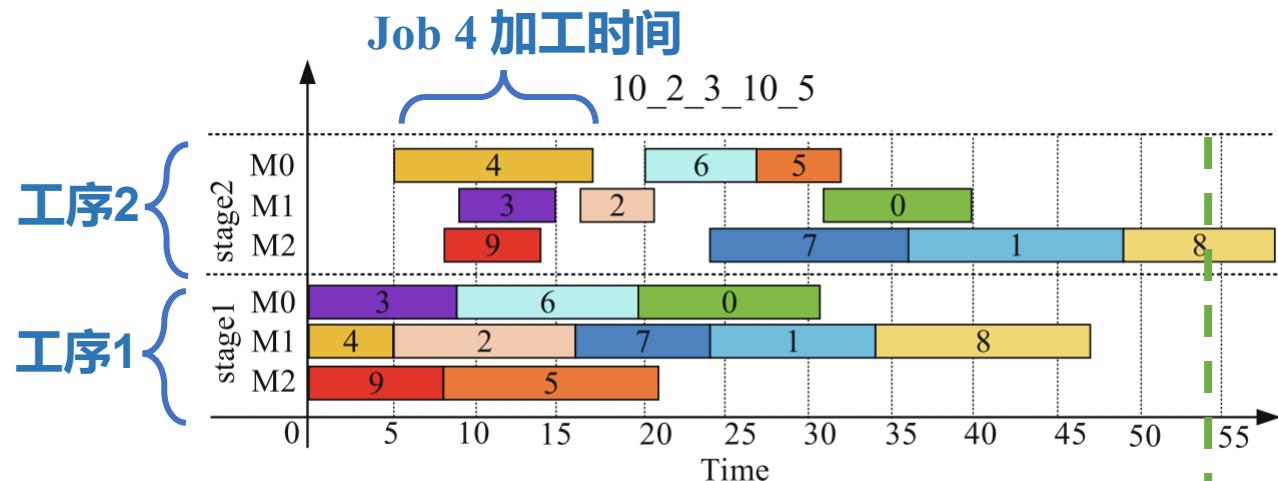
多机型混合：生产柔性，便于订制



流水线：每个工件依照相同次序通过各道工序

[2] Ruiz, R. and Vazquez-Rodriguez, J. A. (2010). "The Hybrid Flow Shop Scheduling Problem." European Journal of Operational Research 205(1): 1-18. DOI: 10.1016/j.ejor.2009.09.024

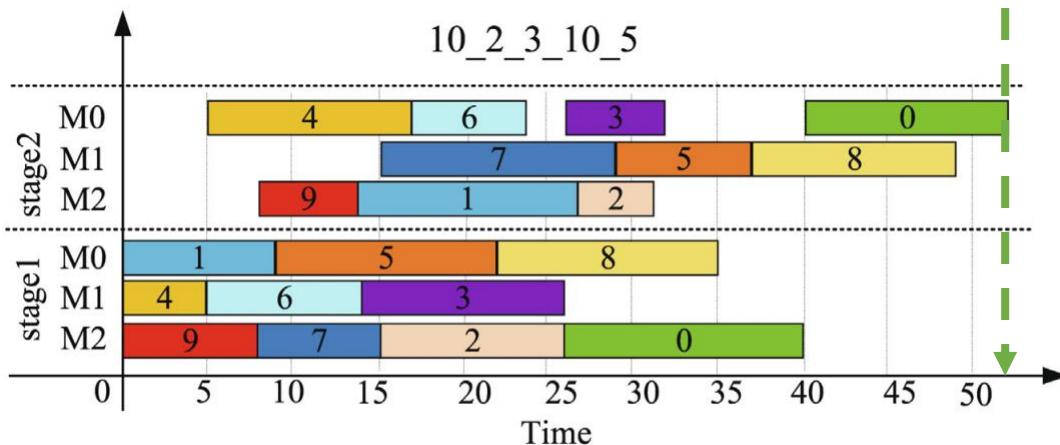
1. 论文引言——问题综述



原方案

延迟时间 33%

能耗成本 25%

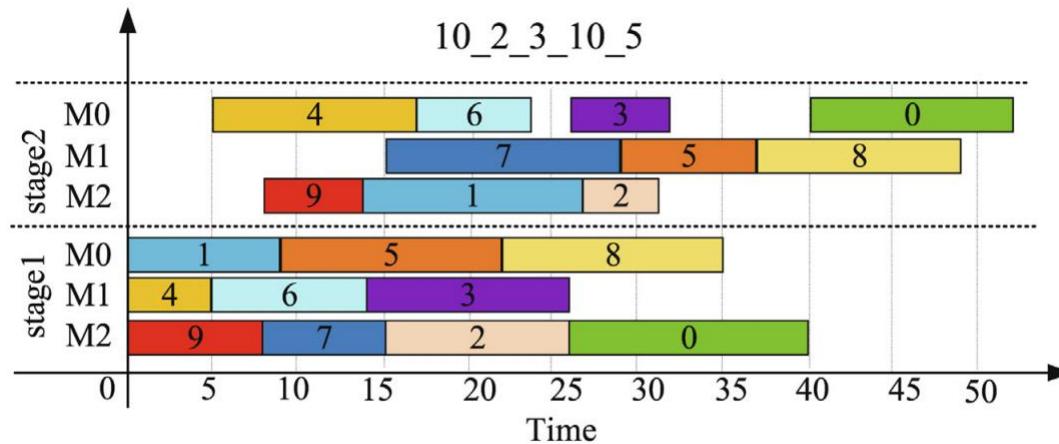
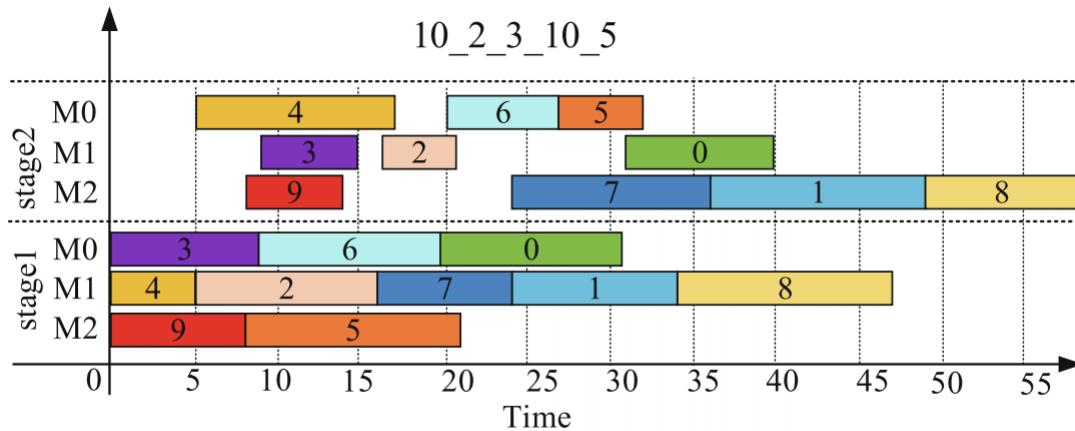


优化后

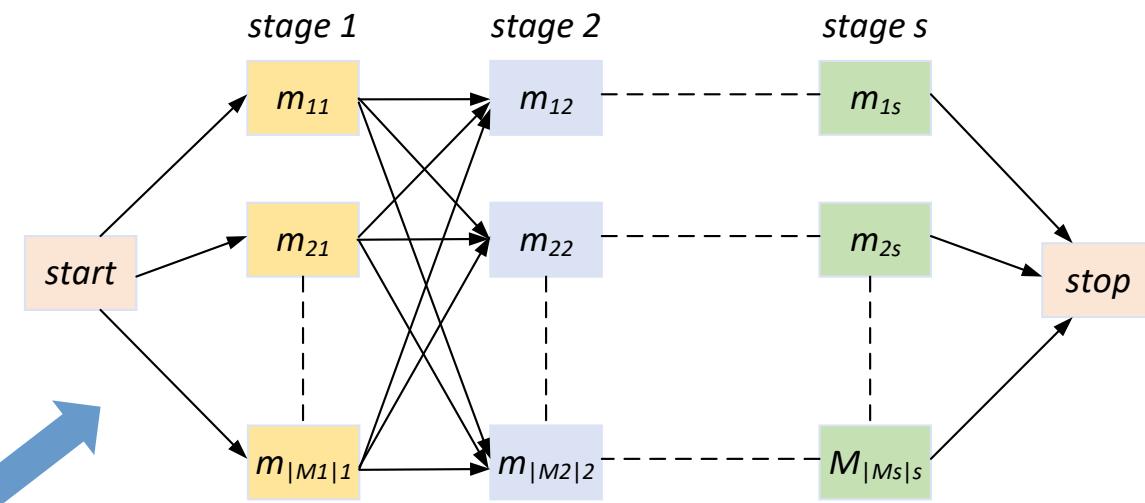
合理的车间调度方案可以
有效减少能耗和完工时间

调度甘特图

1. 论文引言——问题综述



(b) A local optimal solution with TEC of 57355.2 € and TT of 94 h



混合流水线调度优化是把工件按次序分配到不同机器上，用**最少**的资源（时间或能耗等）达到**最大**收益

1. 论文引言——问题综述

Interfaces with Other Disciplines

Learning to select operators in meta-heuristics: An integration of Q-learning into the iterated greedy algorithm for the permutation



1. Introduction

Hybrid flow shop scheduling (HFS) problems are commonly encountered in manufacturing environments. They are extensions of classical flow shop scheduling problems in which a set of jobs need to be processed in a group of machines following the same

production efficiency is essential, by no means should it be the only factor to be considered in manufacturing operations. In recent years, it has been increasingly recognized that economic development without environmental considerations may cause irreversible damage to the world environment. Statistical data shows the Germany industrial sector was responsible for approximately 47%

An energy-efficient two-stage hybrid flow shop scheduling problem in a glass production

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(Received 14 November 2018; accepted 13 May 2019)

Energy-efficient scheduling is highly necessary for energy-intensive industries, such as glass, mould or chemical production. Inspired by a real-world glass-ceramics production process, this paper investigates a bi-criteria energy-efficient two-stage hybrid flow shop scheduling problem, in which parallel machines with eligibility are at stage 1 and a batch machine is at stage 2. The performance measures considered are makespan and total energy consumption. Time-of-use (TOU) electricity prices and different states of machines (working, idle and turnoff) are integrated. To tackle this problem, a mixed integer programming (MIP) is formulated, based on which an augmented ϵ -constraint (AUGMECON) method is adopted to obtain the exact Pareto front. A problem-tailored constructive heuristic method with local search strategy, a bi-objective tabu search algorithm and a bi-objective ant colony optimisation algorithm are developed to deal with medium- and large-scale problems. Extensive computational experiments are conducted, and a real-world case is solved. The results show effectiveness of the proposed methods, in particular the bi-objective tabu search.

Keywords: two-stage hybrid flow shop; total energy consumption; ϵ -constraint method; constructive heuristic; bi-objective tabu search; bi-objective ant colony optimisation

- ✓ 闲置机器能否关机?
- ✓ 所有并行机运行速度是否一致?
- ✓ 考虑分时定价?
- ✓ 多目标问题的算法是否高效?
- ✓ ...



多目标混合流水车间
(MOE-HFS)
节能调度研究

1. 论文引言——创新点

考虑生产和环境效益的MOE-HFS问题研究

- ✓ 大多数调度研究集中于完工时间或拖期的多目标优化，**考虑节能特性的多目标研究较少。**
- ✓ 本文MOE-HFS节能调度问题同时优化了**总拖期、能耗成本和碳交易成本**。
- ✓ 本文考虑**新旧并行机的混用**调度，现有研究往往忽略并行机器的差异性，不能真实反应现实。

1. 论文引言——创新点

考虑生产和环境效益的MOE-HFS问题研究

综合考虑分时电价和开关机节能机制

- ✓ 现有研究通常考虑供给或需求某一方面的节能，协同能源供给和需求节能策略的研究较少，例如在需求侧使用机器速度可调或开关机策略，在供给侧考虑分时电价或实时电价。
- ✓ 本文在模型层面融入供给侧节能机制-**分时电价**和**尖峰电价**，在需求侧融入**开关机节能机制**。

1. 论文引言——创新点

考虑生产和环境效益的MOE-HFS问题研究

综合考虑分时电价和开关机节能机制

强化学习驱动的多目标元启发式算法

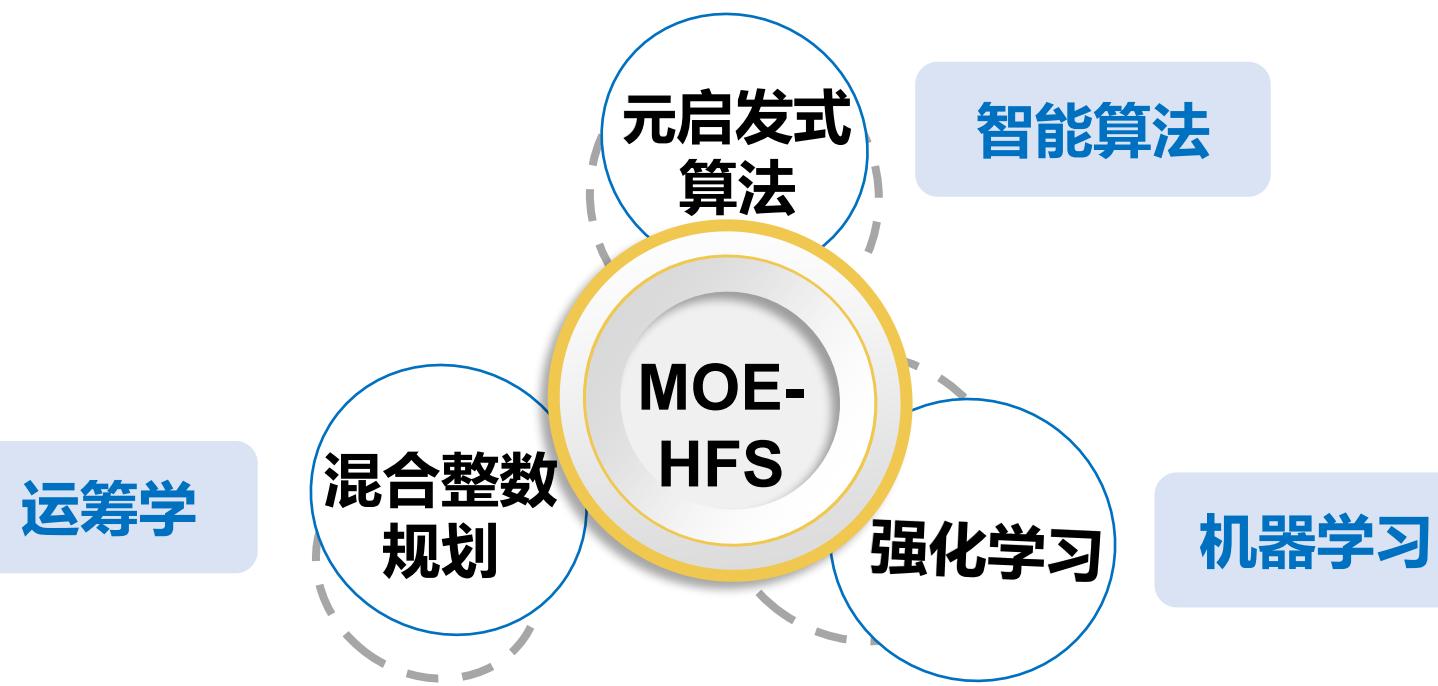
- ✓ 现有研究解决MOE-HFS问题的元启发式算法采用随机搜索，缺少经验引导，容易陷入局部最优，将强化学习引进运筹算法的研究较少。
- ✓ 本文设计了Q-learning算法和可变邻域搜索（Variable neighborhood search, VNS）强化的NSGA-II算法，成功求解了MOE-HFS模型，求解性能优于经典算法NSGA-II和SPEA2，提升了了解的多样性和优越性。

1. 论文引言——创新点

考虑生产和环境效益的MOE-HFS问题研究

综合考虑分时电价和开关机节能机制

强化学习驱动的多目标元启发式算法





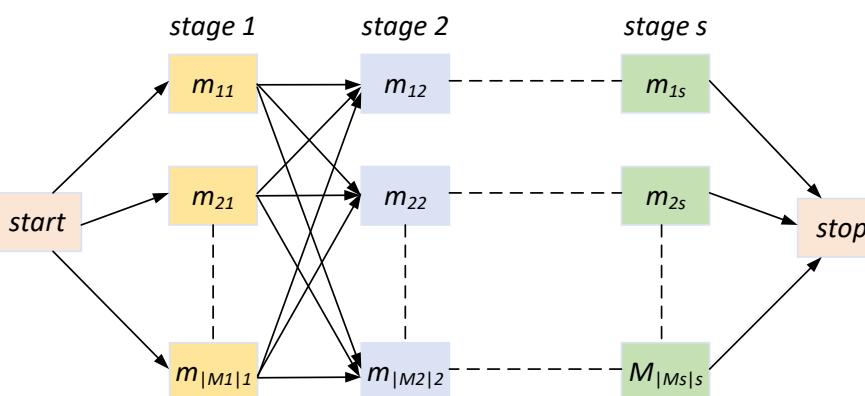
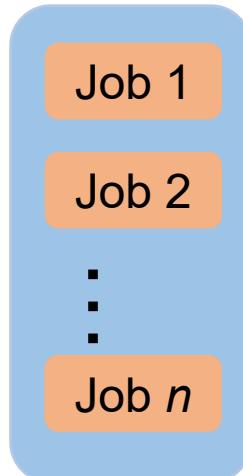
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第二部分 | 问题建模

2. 问题建模

问题假设

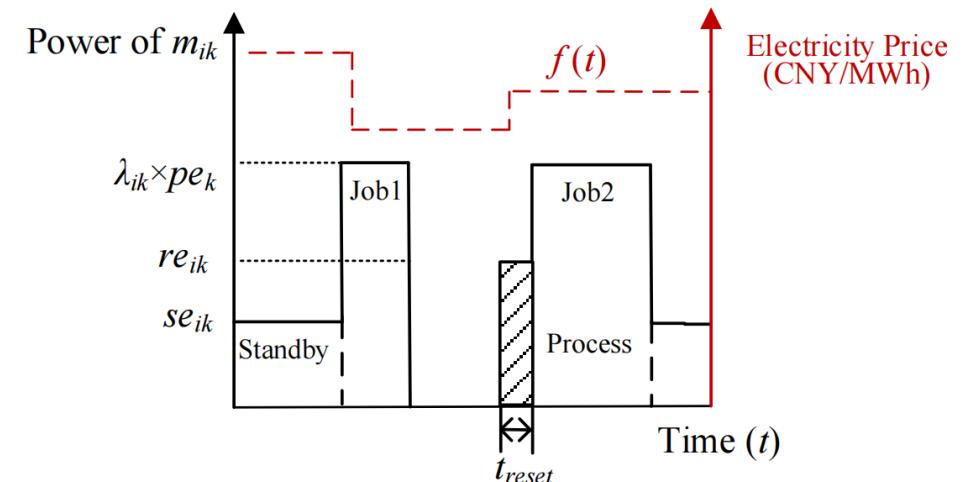
- (1) 机器和工作在时间 0 可用。
- (2) 每个作业一次只能在一台机器上处理。
- (3) 每台机器一次最多只能处理一个作业。
- (4) 作业一旦开始就不能中断。



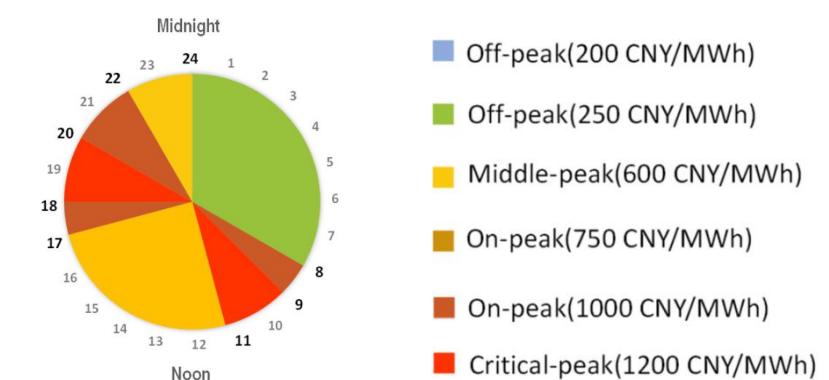
机器 m_{ik} : 运行速度, 运行/待机/重启状态的功率

作业 j : 到货期, 每道工序的工时

开关机节能机制



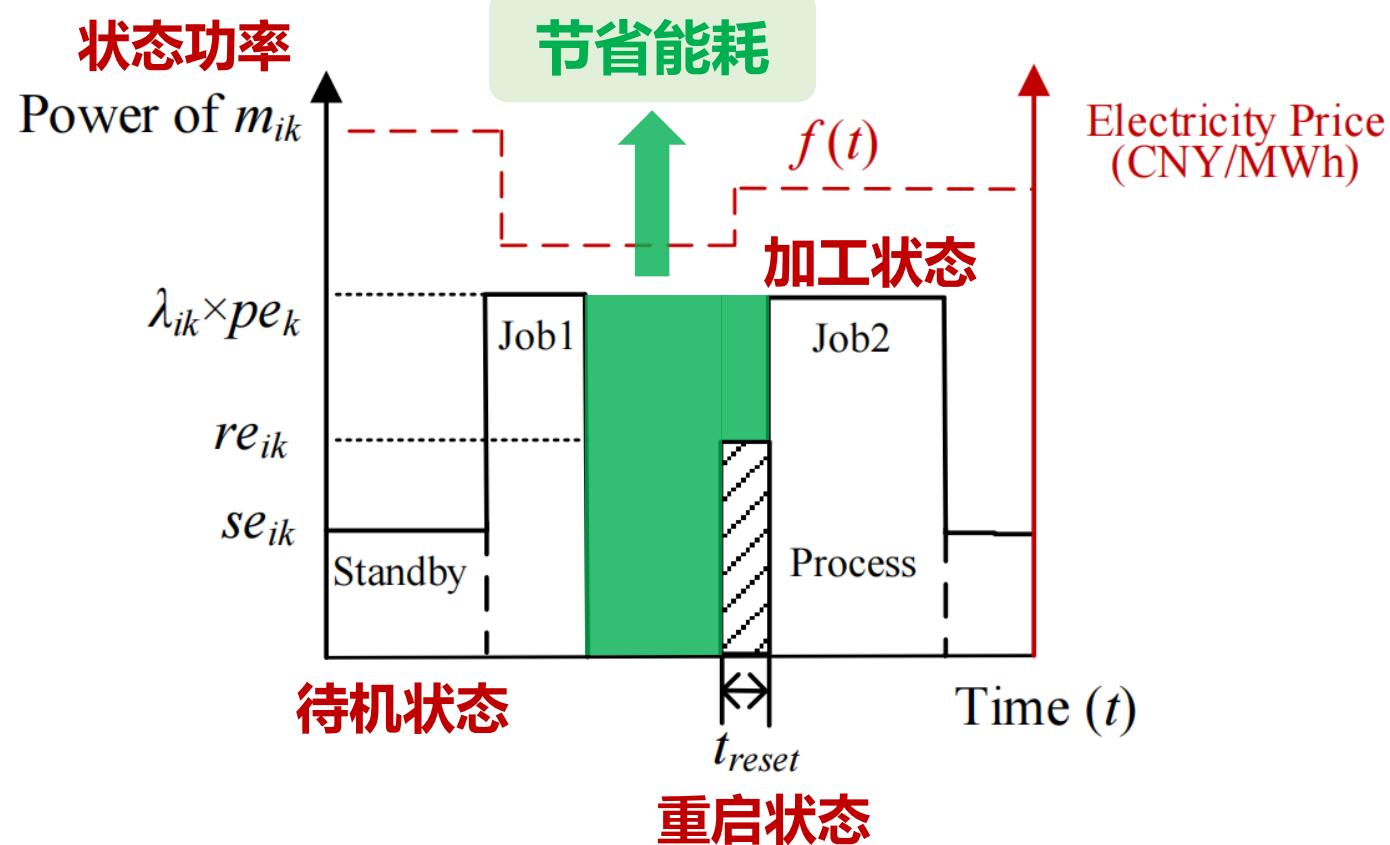
分时电价机制



2. 问题建模

开关机节能机制

开关机节能机制通过**关闭待机的机器**，在下一个作业到来之前**重启机器**节省用电能耗。



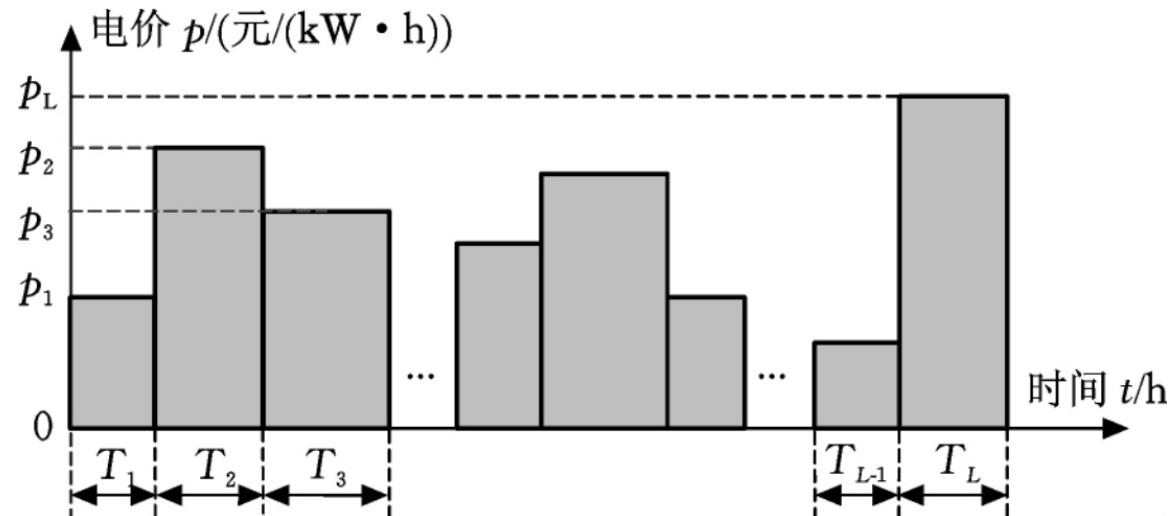
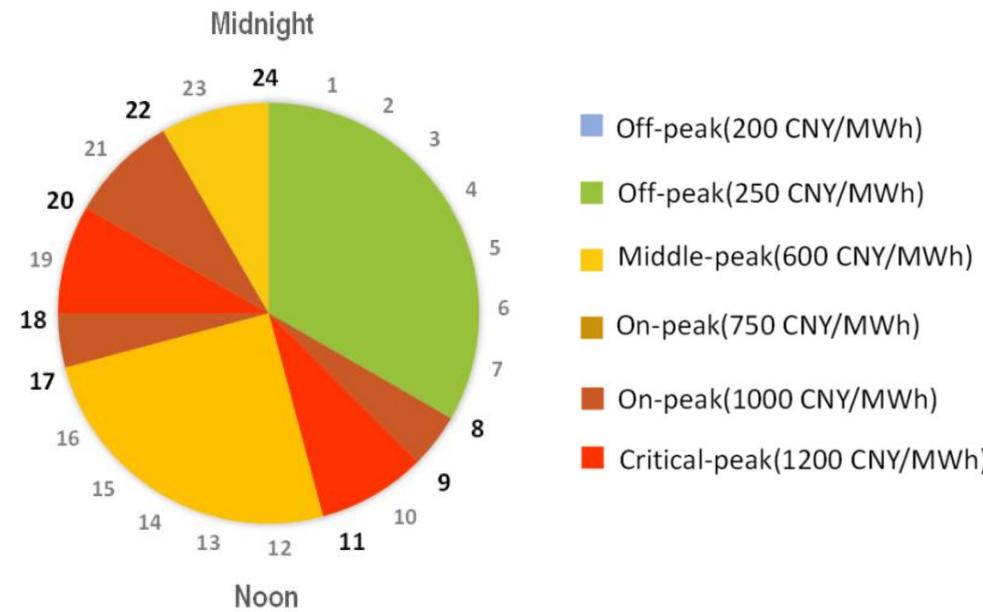
机器运行状态

x_{ik}^t	y_{ik}^t	State	Power
1	1	Processing	pe_{ik}
1	0	Idle	se_{ik}
0	1	Reset	re_{ik}
0	0	Shutdown	0

0-1决策变量 x_{ik}^t, y_{ik}^t 指代任意时刻 t 机器 m_{ik} 的运行状态。

2. 问题建模

分时电价机制



- ✓ 分时电价机制考虑工业用电的波峰波谷，**一天内每个时段电价不同。**
- ✓ 若避开电价高峰选在**低谷时段**加工，则加工能耗**成本会降低**，但可能会**延长交货期**，找出多目标的最佳组合**更加复杂**。

2. 问题建模

优化目标

总拖期
(Total tardiness, TT)

$$TT = \sum_{j \in J} \left(\max \{0, C_{js} - d_j\} \right)$$

分时电价机制

总能耗成本
(Total energy cost, TEC)

$$TEC = \sum_{t \in N} f(t) \sum_{k \in S} \sum_{i \in M_k} E_{ik}^t$$

碳交易成本
(Carbon trading cost, CTC)

$$CTC = [\sum_{t \in N} \sum_{k \in S} \sum_{i \in M_k} (E_{ik}^t \times \mu) - EA] \times C_p$$

开工约束

$$\sum_{t \in N} b_{ik0}^t = 1, i \in M_k, k \in S$$

$$b_{ikj}^1 = a_{ikj}^1, i \in M_k, j \in J, k \in S$$

$$b_{ikj}^t \geq a_{ikj}^t - a_{ikj}^{t-1}, i \in M_k, j \in J, k \in S, t > 1$$

约束条件

$$\sum_{k \in S} \sum_{i \in M_k} \sum_{j \in J} a_{ikj}^t \leq 1, t \in N$$

指定作业约束

$$\sum_{t \in N} \sum_{i \in M_k} b_{ikj}^t = 1, j \in J, k \in S$$

连续流约束

$$\sum_{t \in N} a_{ikj}^t = \sum_{t \in N} b_{ikj}^t \times \frac{p_{jk}}{v_{ik}}, i \in M_k, j \in J, k \in S$$

$$x_{ik}^t y_{ik}^t = \sum_{i \in I} a_{ikj}^t, i \in M_k, k \in S, t \in N$$

加工状态定义

2. 问题建模

优化目标

总拖期
(Total tardiness, TT)

$$TT = \sum_{j \in J} (\max \{0, C_{js} - d_j\})$$

总能耗成本
(Total energy cost, TEC)

$$TEC = \sum_{t \in N} f(t) \sum_{k \in S} \sum_{i \in M_k} E_{ik}^t$$

碳交易成本
(Carbon trading cost, CTC)

$$CTC = [\sum_{t \in N} \sum_{k \in S} \sum_{i \in M_k} (E_{ik}^t \times \mu) - EA] \times C_p$$

约束条件

$$i \in M_k, k \in S, t \in N, h \in J$$

$$E_{ik}^t = x_{ik}^t (1 - y_{ik}^t) s e_{ik} + y_{ik}^t (1 - x_{ik}^t) r e_{ik} + \sum_{j \in J} a_{ijk}^t \lambda_{ik} p e_k$$

开关机能耗定义

待机

重启

加工

$$\sum_{h \in J \cup \{0\}} \chi_{iljh} = \sum_{t \in N} b_{ikj}^t, i \in M_k, j \neq h, j \in J$$

$$\sum_{j \in J \cup \{0\}} \chi_{iljh} = \sum_{t \in N} b_{ikh}^t, i \in M_k, j \neq h, h \in J$$

紧前紧后约束

$$S_{jk} = \sum_{i \in M_k} (\sum_{t \in N} b_{ikj}^t \times t)$$

$$C_{jk} = \sum_{i \in M_k} (\sum_{t \in N} b_{ijk}^t \times (t + \frac{p_{jk}}{v_{ik}} - 1))$$

$$C_{hk} - \frac{p_{hk}}{v_{ik}} - C_{jk} \geq B(\chi_{iljh} - 1)$$

$$C_{jk} \leq S_{j(k+1)}$$

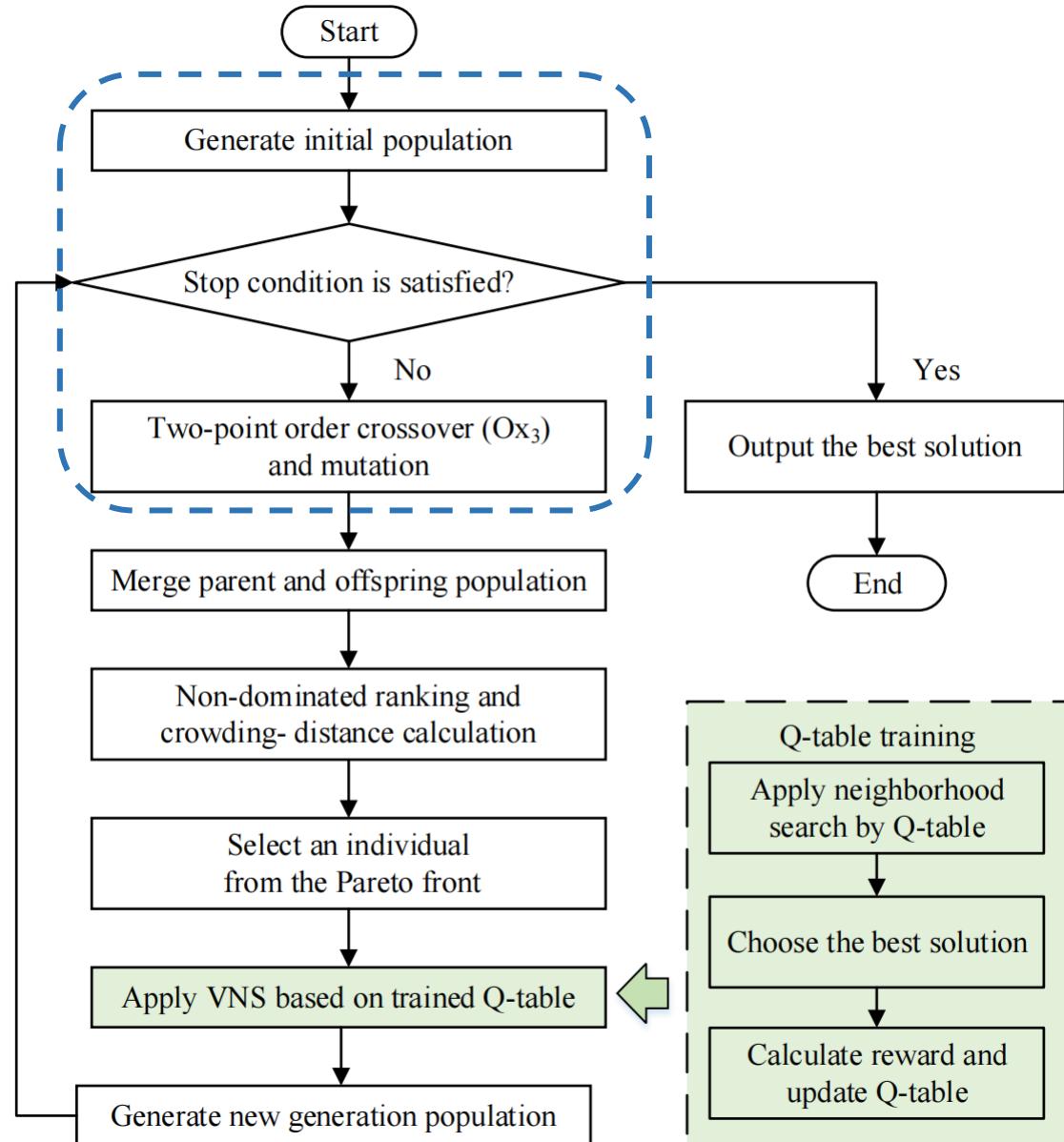
加工时间约束



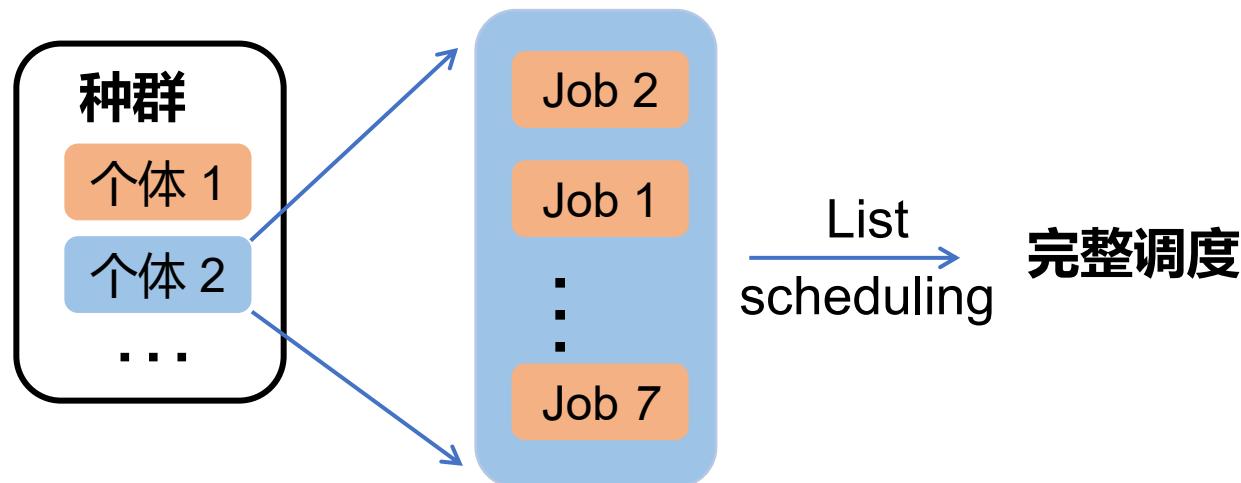
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第三部分 | QVNS-NSGA-II

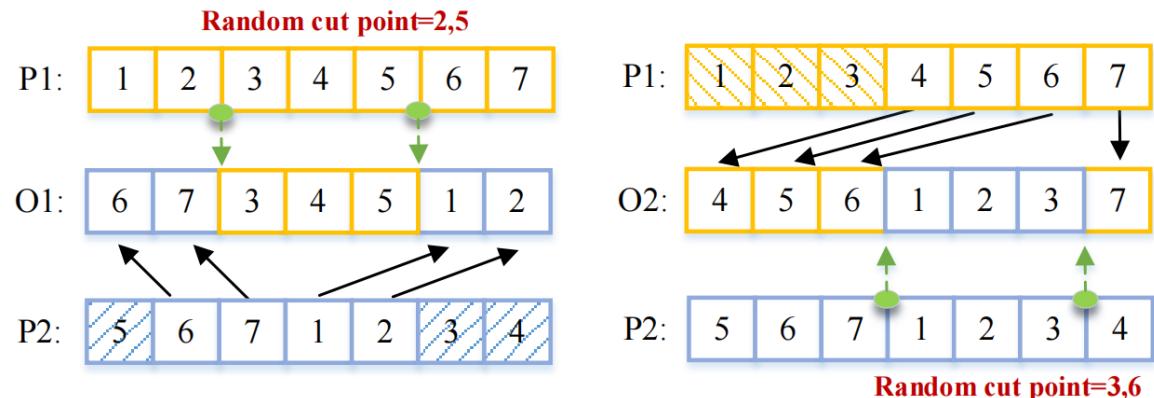
3. QVNS-NSGA-II: 快速非支配排序基因算法NSGA-II



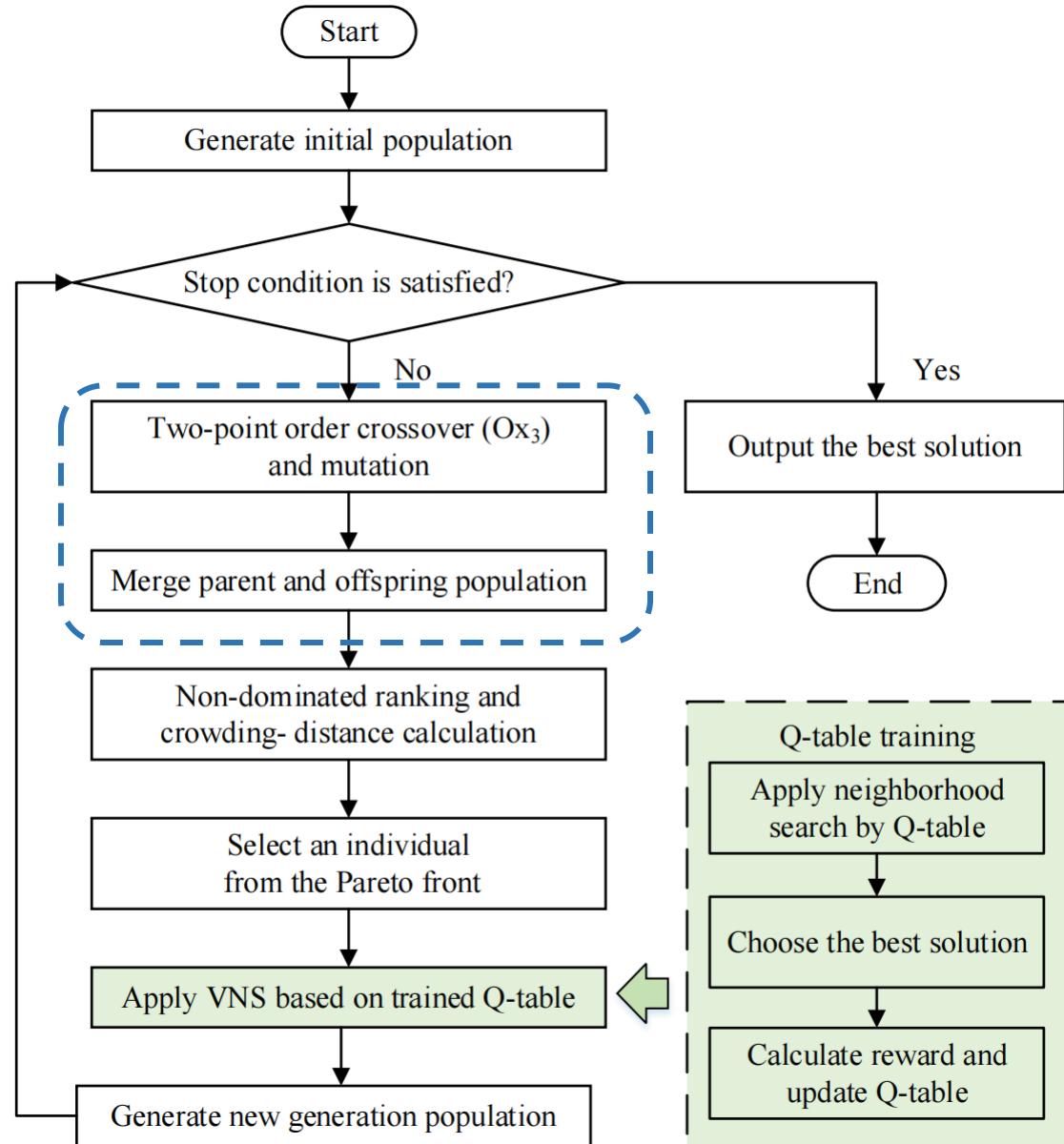
(1) 种群和个体



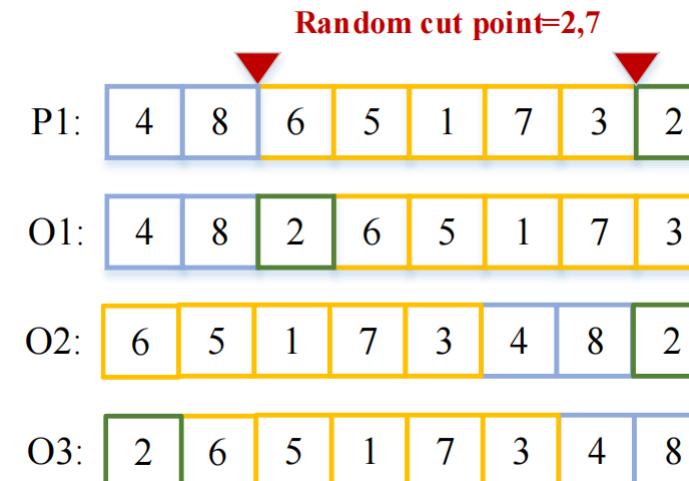
(2) 两点有序交叉



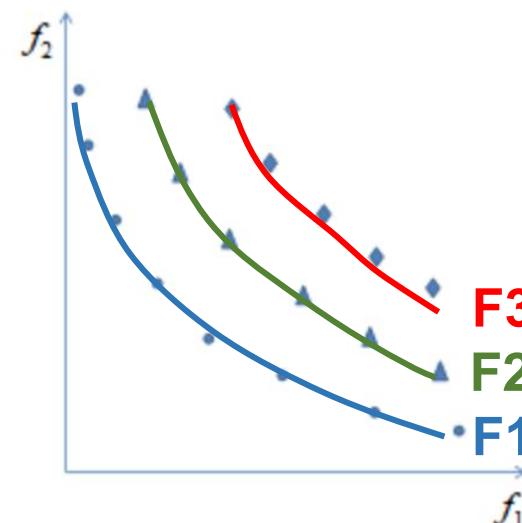
3. QVNS-NSGA-II: 快速非支配排序基因算法NSGA-II



(3) 有序交叉变异



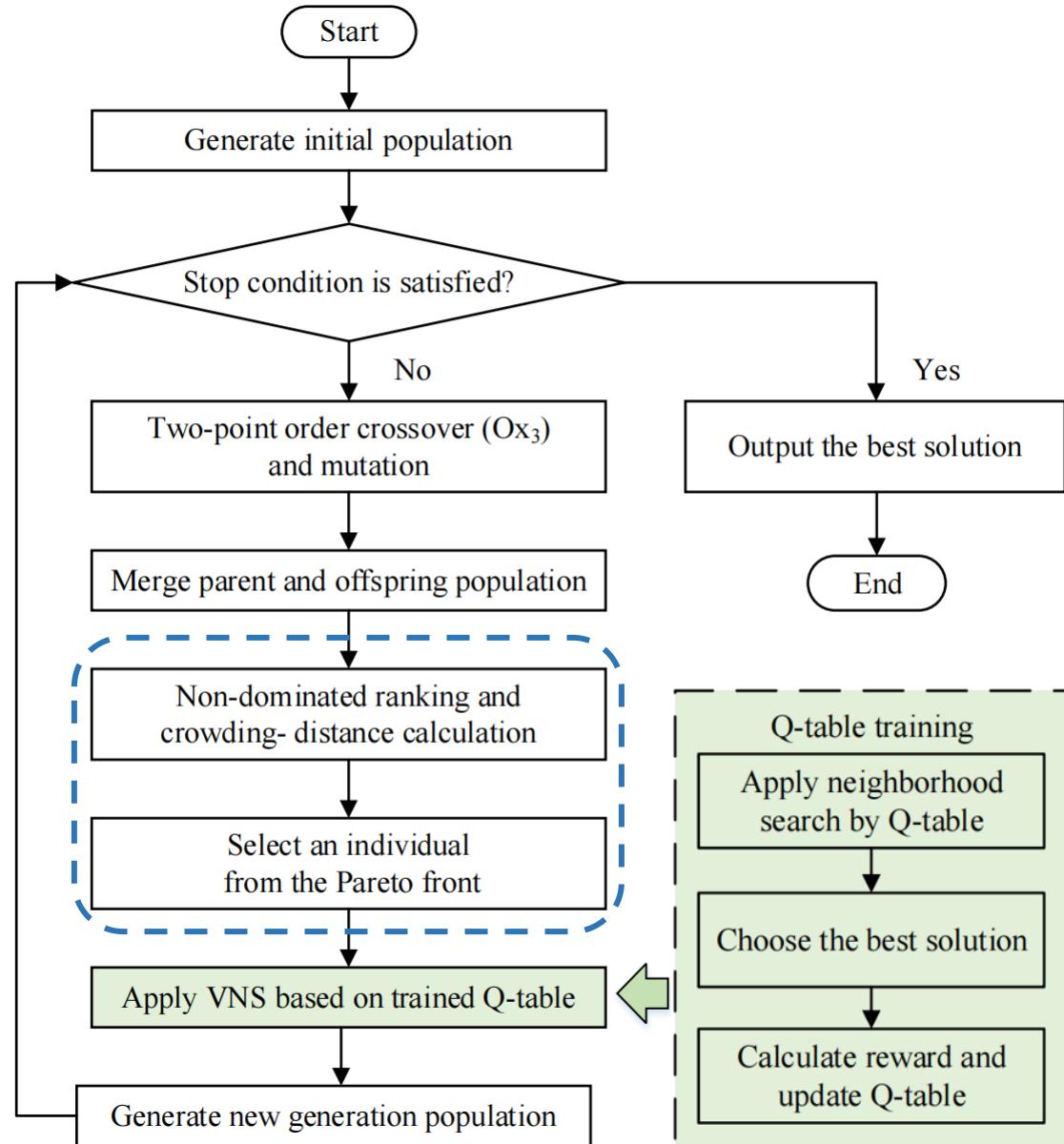
(4) 非支配排序



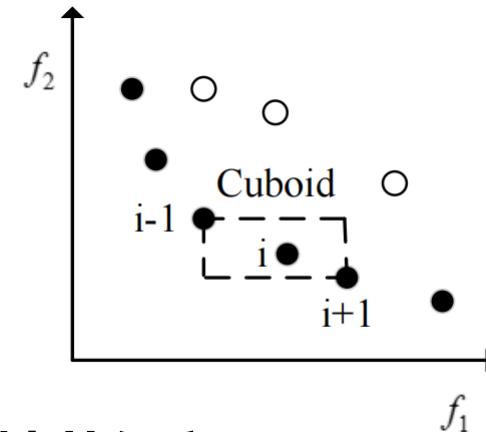
多目标非支配排序
若解1所有目标函数小
于解2，则称1支配2

F1不被任何解支配，
称为Pareto Set

3. QVNS-NSGA-II: 快速非支配排序基因算法NSGA-II

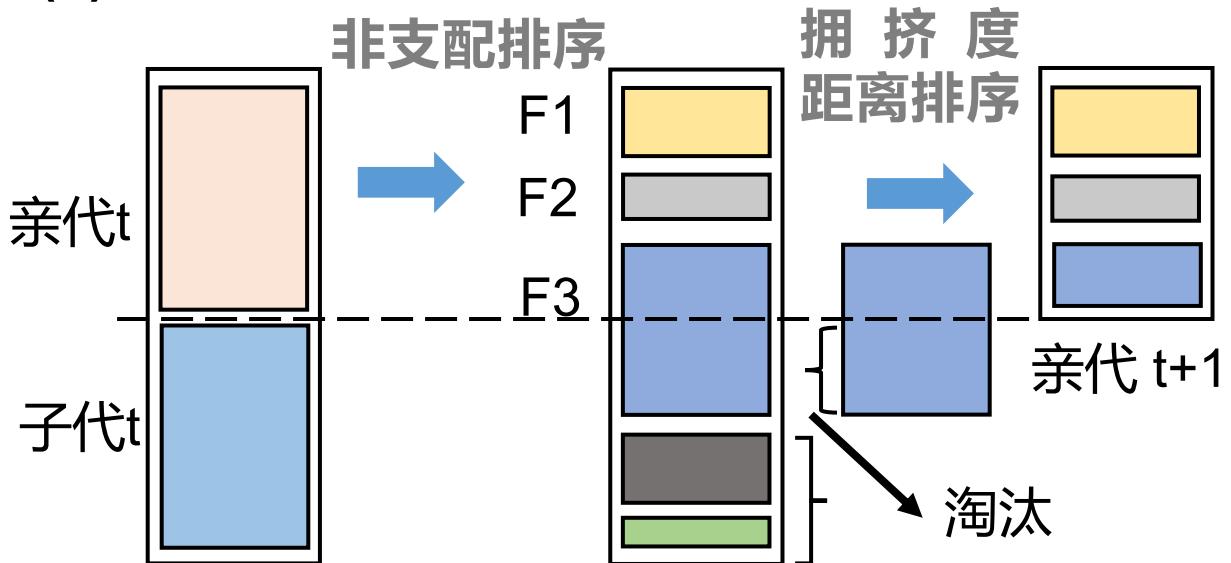


(5) 拥挤度距离排序



同一层里解的拥挤度距离越大，解的质量越高

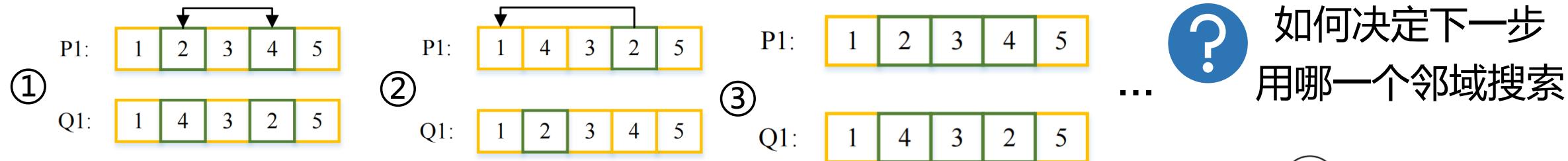
(6) 精英保留



3. QVNS-NSGA-II: Q-learning 驱动 VNS

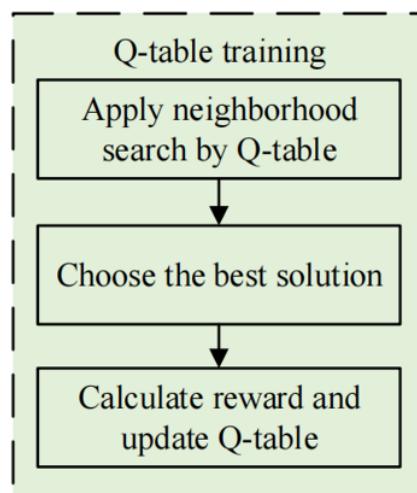
(7) Variable neighborhood search (VNS)

VNS 通过系统地改变**邻域**以逃避局部最优，通常使用**随机选择**，缺少知识指导



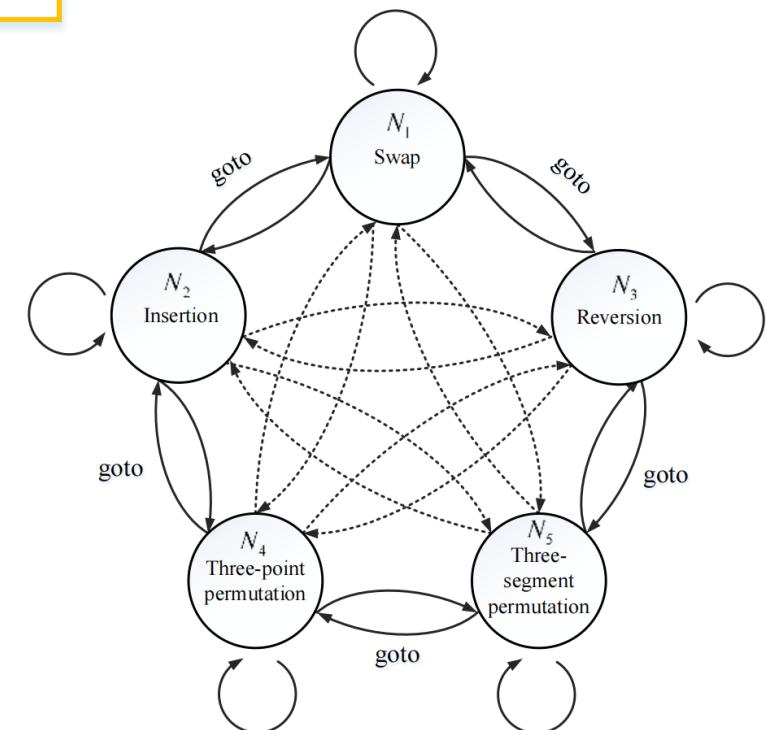
(8) Q-learning: 利用训练的经验引导VNS选择合适邻域搜索

马尔科夫链



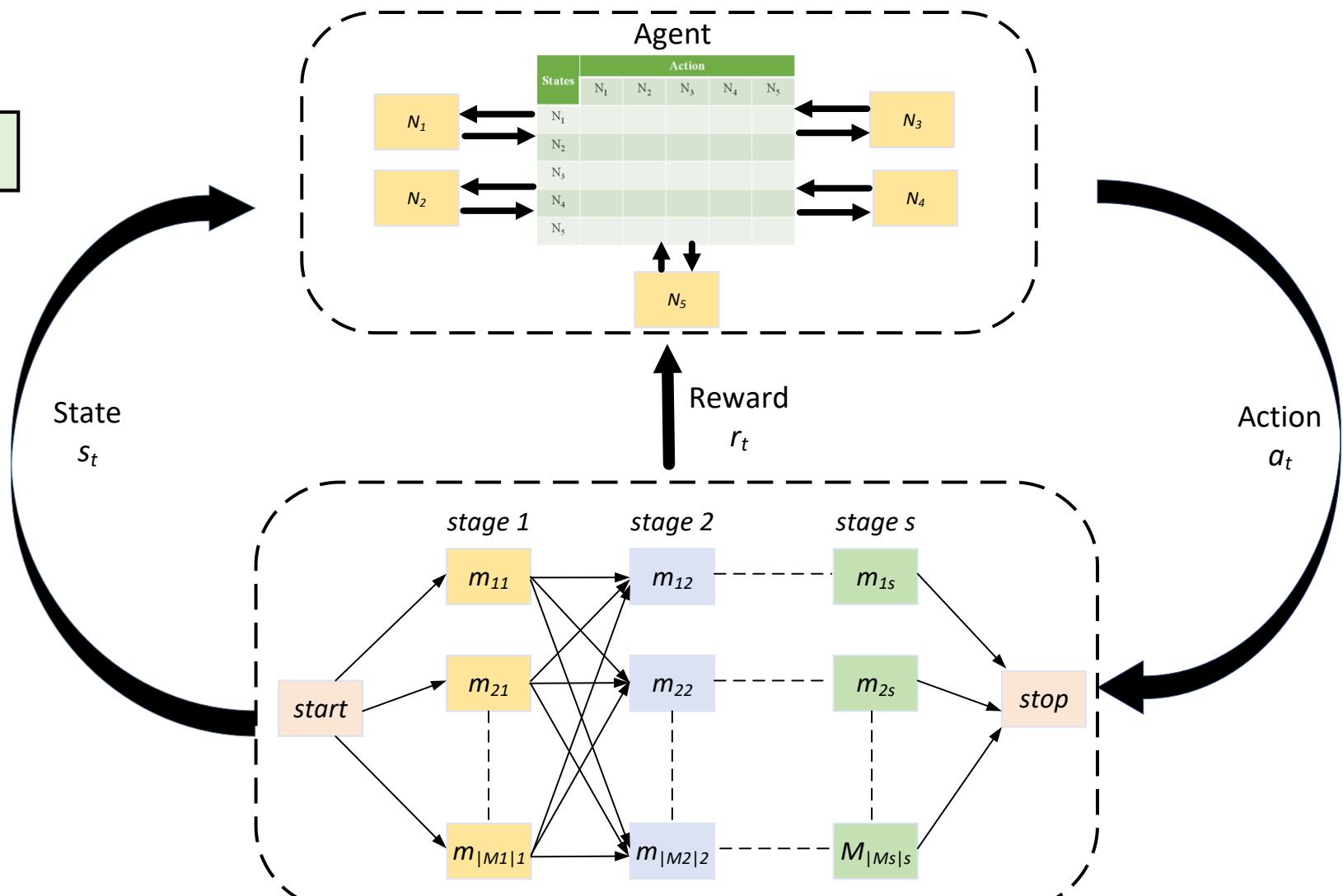
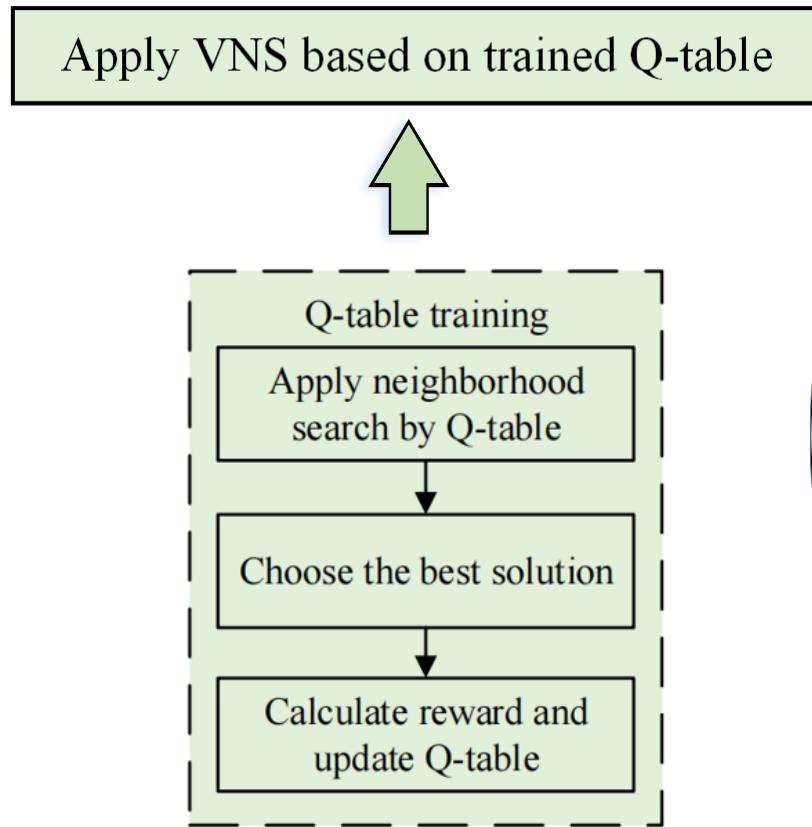
$$Q(s, a) \leftarrow Q(s, a) + \alpha \left[r + \gamma \max_{a'} Q(s', a') - Q(s, a) \right]$$

States	Actions				
	N_1	N_2	N_3	N_4	N_5
N_1	0	0	0	0	0
N_2	0	0	0	0	0
N_3	0	0	0	0	0
N_4	0	0	0	0	0
N_5	0	0	0	0	0



3. QVNS-NSGA-II: Q-learning 驱动 VNS

(9) Q-learning 驱动 VNS: 强化学习驱动的NSGA-II算法，高效求解多目标调度





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第四部分 | 数值实验

4. 数值实验

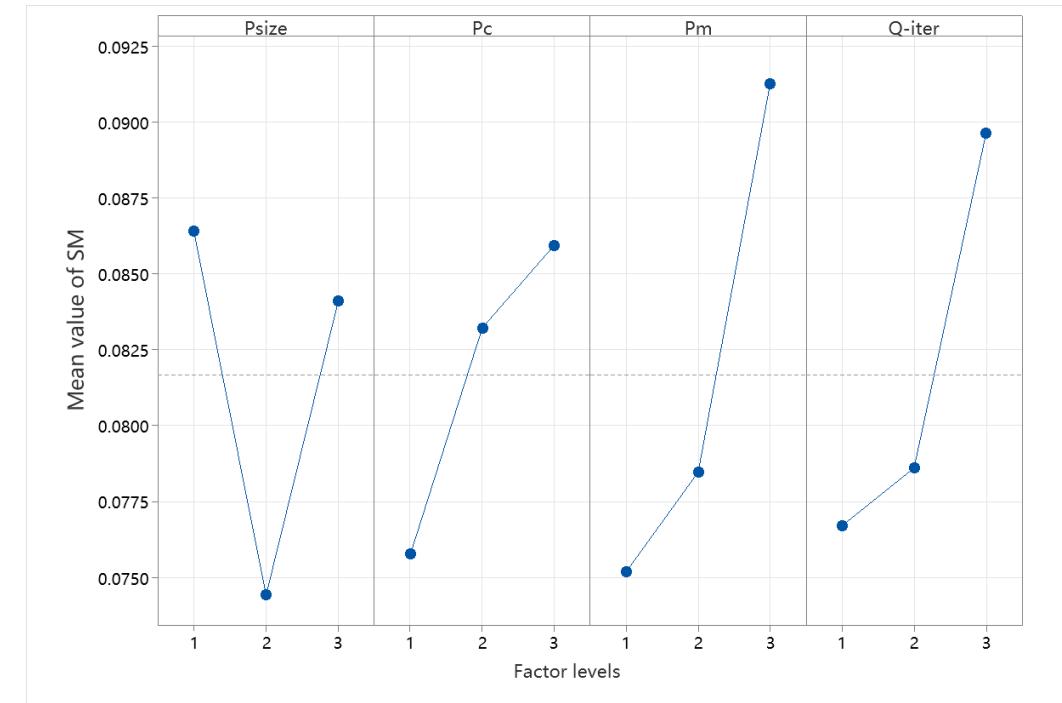
(1) 参数设定

Factors	Levels
Number of jobs	10, 20, and 50
Number of stages	3, 5
Number of machines at each stage	3, 4, 6
Processing time of each operation	$U[5,10]$ (hour)
Power of machine	$U[5,10](10^5 \text{ W})$
Processing speed	{1.2, 1.0, 0.8} (Mansouri et al. 2016)
Conversion rate	{1.5, 1.0, 0.6} (Mansouri et al. 2016)
Standby power of machine	2
Reset power of machine	4
Carbon emission coefficient	0.2 (ton / MWh)
Price of carbon emissions	30 (CNY/ton)
Emission Allowance	1 ton / (job · stage)

(2) 算法性能指标

- Number of Pareto solutions (NPS) ↑
- Spacing matrix(SM) ↓

$$SM = \sqrt{\frac{\sum_{i=1}^A (d_i - \bar{d})^2}{|A|}}$$

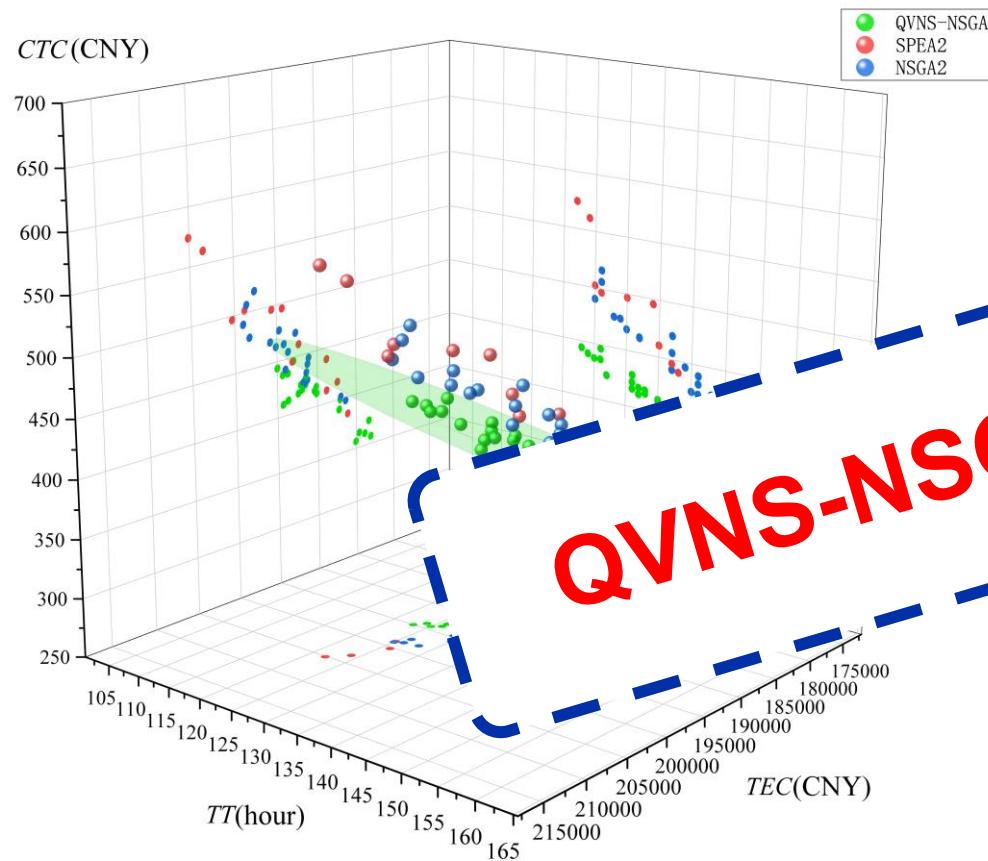


- Running time (RM) ↓
- Coverage metric (CM) ↑

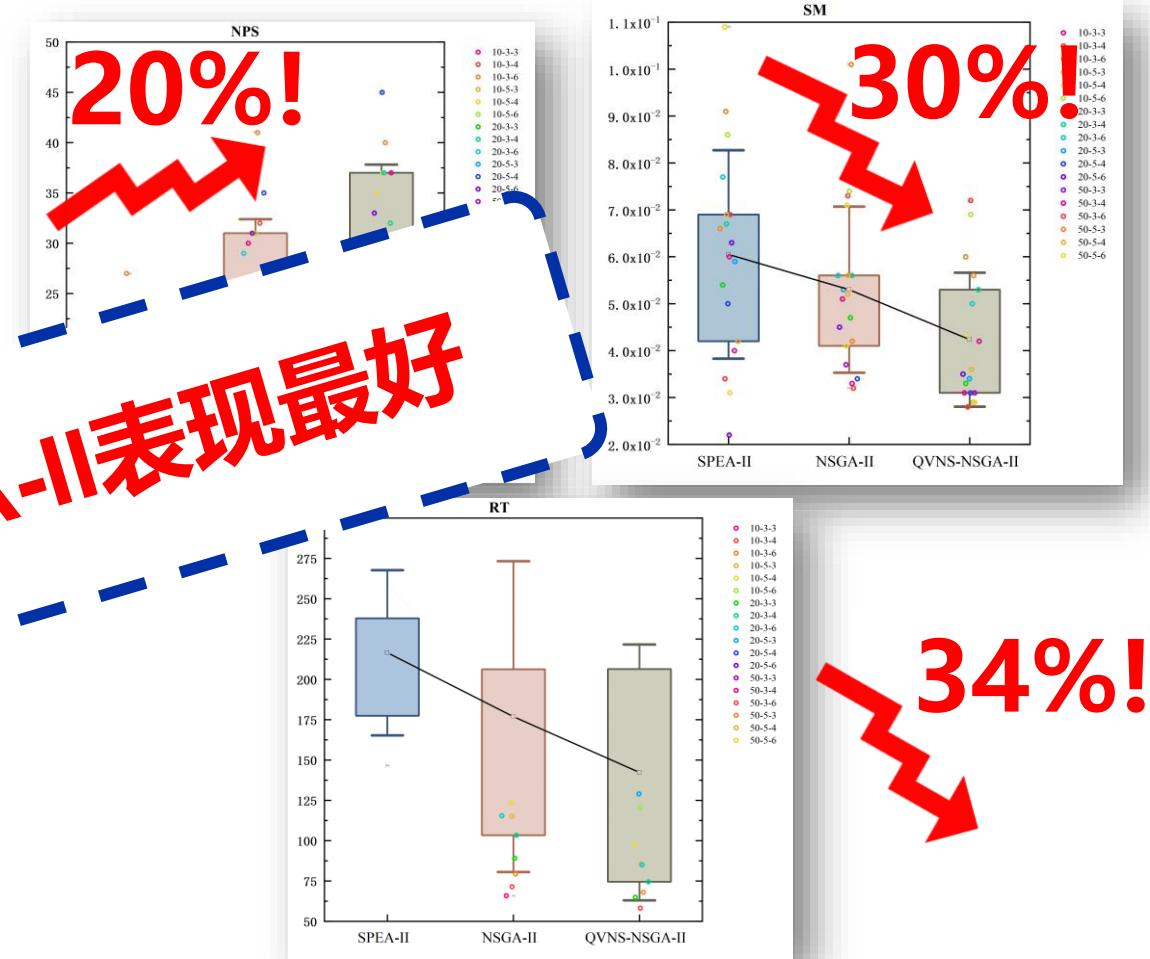
$$C(A, B) = \frac{\left| \left\{ b \in B \mid \exists a \in A : a \neq b \text{ or } a = b \right\} \right|}{|B|}$$

4. 数值实验-实验结果

(3) 实验结果



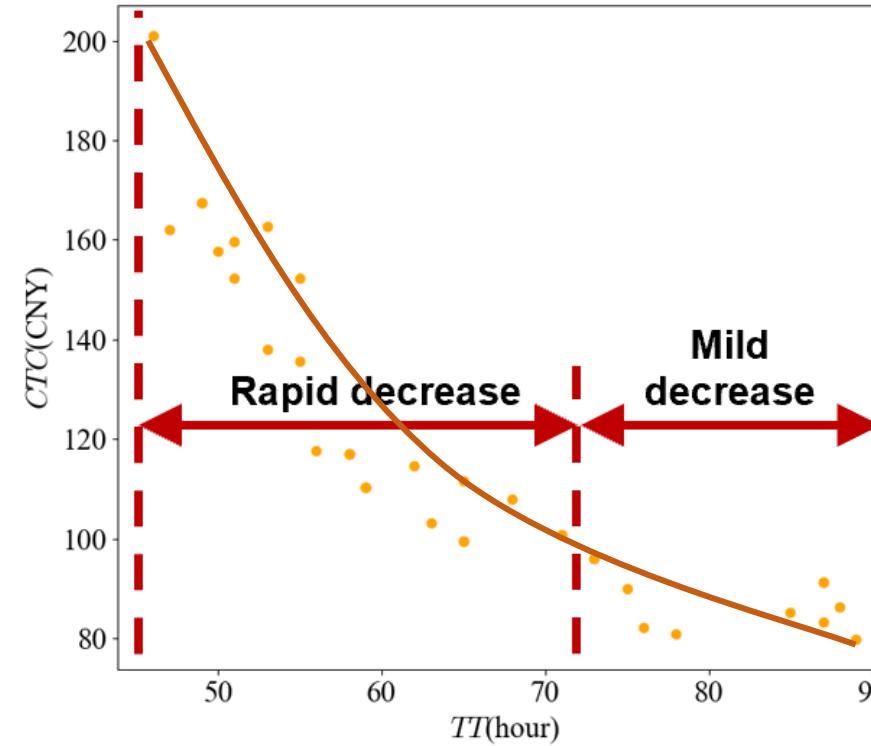
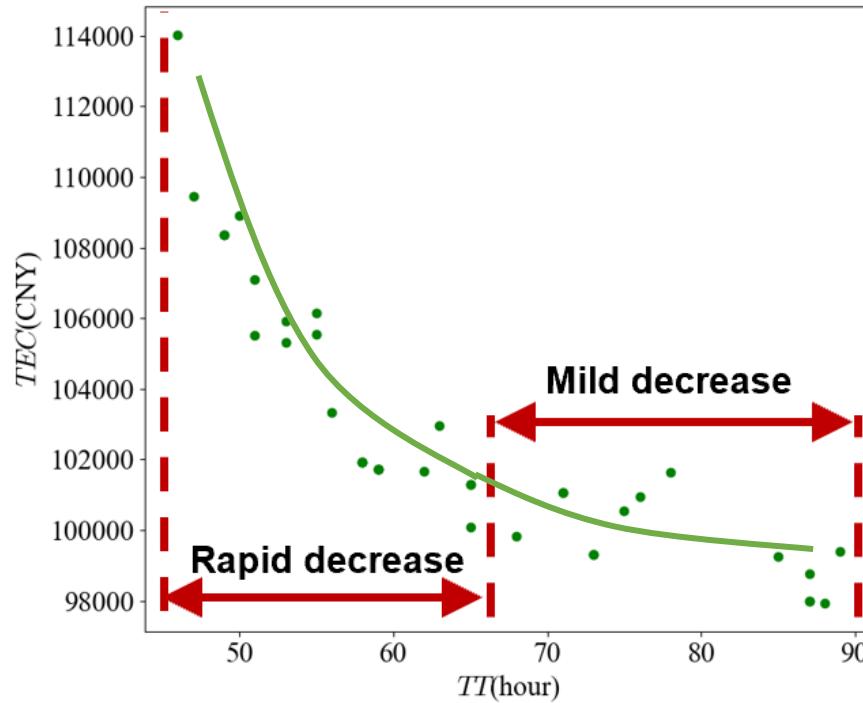
QVNS-NSGA-II 表现最好



QVNS-NSGA-II 在求解的数量、质量和计算效率上均显著优于 NSGA-II, SPEA-II

4. 数值实验-灵敏度分析

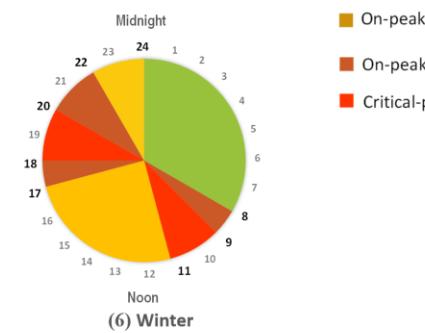
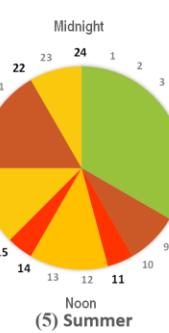
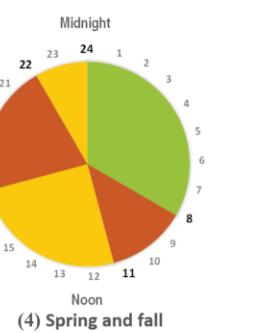
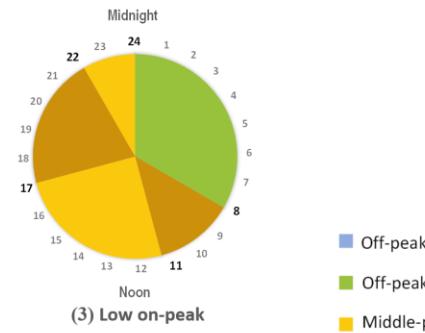
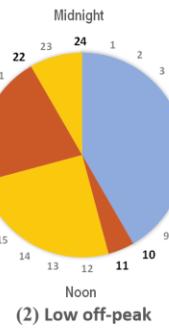
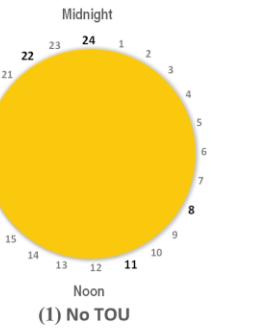
(4) 灵敏度分析-多目标制衡



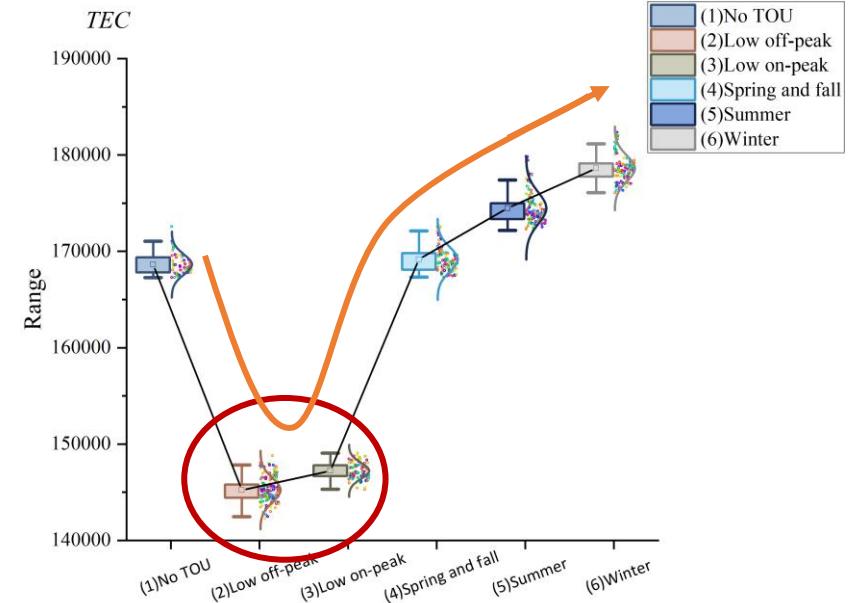
- ✓ 三个目标之间**相互制约**，能耗成本/碳交易成本的**下降**引起总拖期的**延长**；
- ✓ 下降的速度分为**快速下降**和**平稳下降**两个阶段，决策者应分阶段考虑

4. 数值实验-灵敏度分析

(4) 灵敏度分析-不同分时电价下的差异



- Off-peak(200 CNY/MWh)
- Off-peak(250 CNY/MWh)
- Middle-peak(600 CNY/MWh)
- On-peak(750 CNY/MWh)
- On-peak(1000 CNY/MWh)
- Critical-peak(1200 CNY/MWh)



管理建议

制造商应将更多订单分配到具有特定分时电价的季节，这样既可以节省能耗成本，又保持相对稳定的总拖期和碳交易成本。



第五部分 | 总结与展望

5. 总结展望



结论

- 协同考虑分时电价和开关机节能机制可以有效节能；
- 提出QVNS-NSGA-II 能够比 NSGA-II 和 SPEA-II 更快地找到质量更高的解决方案；
- 决策者应该在多目标之间做出妥协，将更多订单分配到具有特定分时电价的季节以节省总能耗成本。



未来展望

- 元启发式算法和强化学习的集成是一个很有前途的方向，可以扩展研究更多的生产调度问题。
- 在所提出的模型中考虑新的节能机制，如机器速度可调机制和实时定价。
- 提出的模型和算法在实际生产环境中的应用前景广阔。

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基于强化学习驱动NSGA-II算法的 多目标混合柔性流水车间调度研究

Muti-objective energy-efficient hybrid flow shop scheduling using Q-learning and VNS driven NSGA-II

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