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A review of flexible job shop scheduling problems considering transportation vehicles

Key words: Flexible manufacturing system; Transportation vehicle; Processing machine; Integrated scheduling

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Motivation

1. Industry 4.0-driven manufacturing transformation

- Global initiatives (e.g., Industry 4.0 in Germany and Made in China 2025) demand flexible, intelligent, and sustainable production systems.
- Rising market needs for mass customization and small-batch production challenge traditional scheduling models.

2. Critical role of material transportation

- Thirty to fifty percent of total production time in flexible manufacturing systems (FMSs) is spent on logistics (e.g., automated guided vehicle movements), yet most studies ignore transportation constraints.
- Coupling of processing and transportation stages directly impacts production efficiency (makespan), cost (energy consumption), and sustainability (carbon footprint).

3. High computational complexity

- NP-hard combinatorial optimization problem:
- Solution space expands exponentially with the increase of problem scale complexity for vehicle-task assignments.
- Simultaneous optimization of machine allocation, operation sequencing, and vehicle scheduling is required.

Main idea

1. Problem overview and modeling

The article reviews the **flexible job shop scheduling problem with transportation vehicles, which integrates machine processing and vehicle transportation scheduling** in FMSs (**FJSP_PT**). It outlines the problem's assumptions, constraints, and objectives. Benchmark datasets are highlighted to evaluate the algorithmic performance.

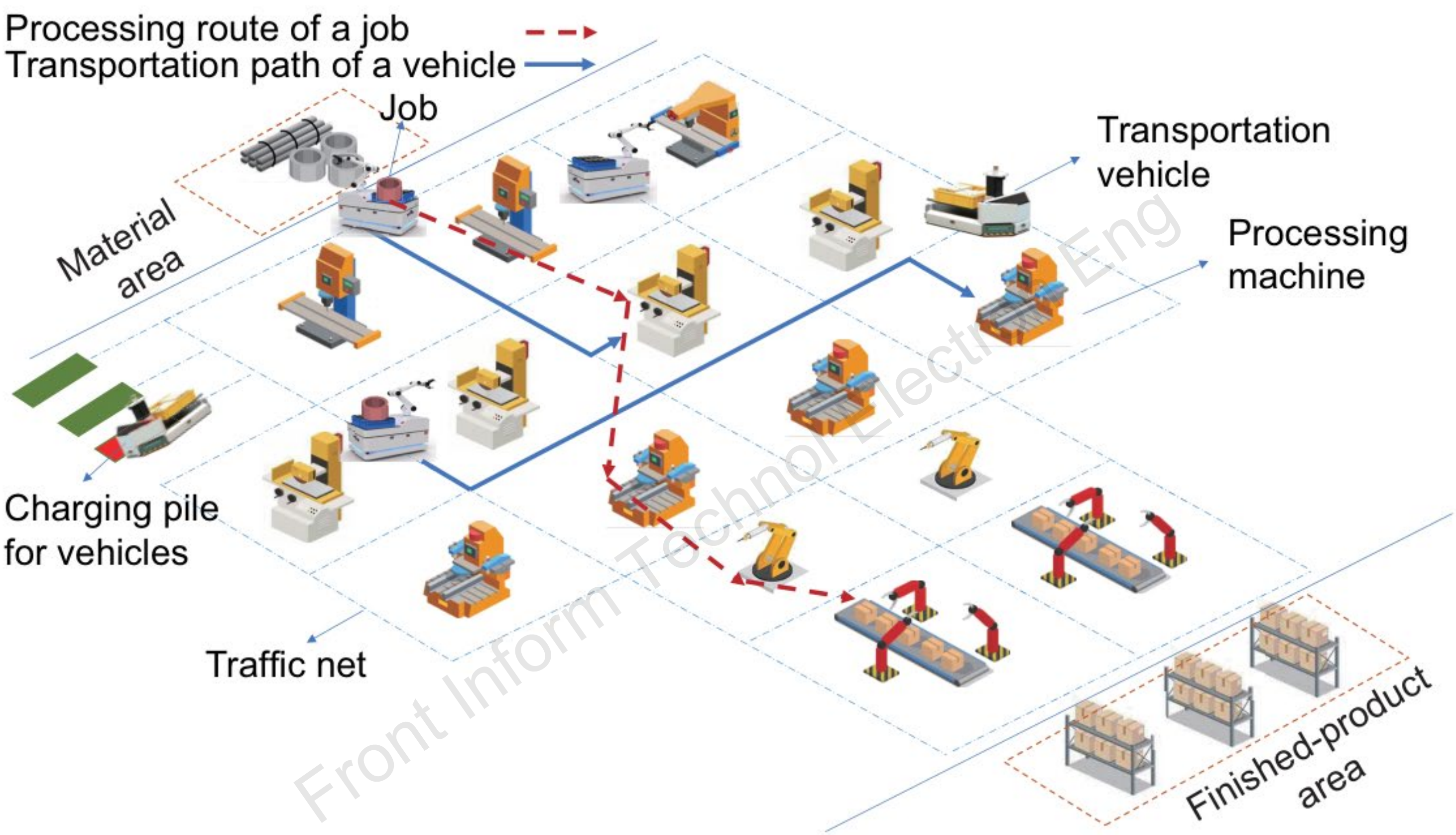
2. Algorithmic approaches and trends

The article categorizes solution methods into **exact algorithms, heuristics, metaheuristics, and swarm intelligence**. Statistical analysis reveals that over 60% of research focuses on metaheuristics and hybrid algorithms, with growing interest in multiobjective and energy-efficient scheduling.

3. Challenges and future directions

Key challenges include scaling solutions for large-scale systems, addressing dynamic uncertainties and balancing conflict. Trends emphasize transition from centralized to distributed scheduling, and from single-objective to green-production multiobjective. The complexity of FJSP_PT and the need for robust, real-time algorithms remain critical research frontiers.

Model of FJSP_PT



1. Job routing
This subproblem involves planning feasible processing routes for jobs across machines.

2. Operation sequencing
This subproblem entails sequencing the operations to be processed on each machine.

3. Transportation task assignment
The transportation tasks will be allocated to different vehicles.

Model of FJSP_PT

Processing sequence constraint: The sequence of operations for each job must adhere to a specific technological route, like constraints (A3) and (A4).

Equipment utilization constraint: Machines and vehicles can handle only one job at a time, like constraint (A5).

Job utilization constraint: Each job can be present in a specific machine or vehicle at any time, like constraint (A16).

Equipment space constraint: Machines situated in different locations result in time consumption for vehicles traveling among them, like constraint (A18).

Task logical constraint: Before each process is carried out, it needs to be transported to the designated processing machine by a vehicle, like constraint (A21).

$$\text{Minimize } C_{\max} \tag{A1}$$

s.t.

$$C_{\max} \geq T^{\mathrm{ep}}_{jN_j^{\mathrm{opr}}}, \forall j \in J, \tag{A2}$$

$$\sum_{i_1 < i \in O_j^{\mathrm{opr}}} \sum_{m \in M} Y^m_{ji_1,ji} + \sum_{j_1 \in J \setminus \{j\}} \sum_{i_1 \in O_{j_1}^{\mathrm{opr}}} \sum_{m \in M} Y^m_{j_1 i_1, ji} + \sum_{m \in M} B^m_{ji} = 1, \forall j \in J, i \in O_j^{\mathrm{opr}}, \tag{A3}$$

$$\sum_{i_1 > i \in O_j^{\mathrm{opr}}} \sum_{m \in M} Y^m_{ji_1,ji} + \sum_{j_1 \in J \setminus \{j\}} \sum_{i_1 \in O_{j_1}^{\mathrm{opr}}} \sum_{m \in M} Y^m_{j_1 i_1, ji} + \sum_{m \in M} L^m_{ji} = 1, \forall j \in J, i \in O_j^{\mathrm{opr}}, \tag{A4}$$

$$\sum_{j \in J} \sum_{i \in O_j^{\mathrm{opr}}} B^m_{ji} \leq 1, \forall m \in M, \tag{A5}$$

$$\sum_{j_1 \in J} \sum_{i_1 \in O_j^{\mathrm{opr}}} L^m_{j_1 i_1} \leq \sum_{j_2 \in J} \sum_{i_2 \in O_{j_2}^{\mathrm{opr}}} B^m_{j_2 i_2}, \forall m \in M, \tag{A6}$$

$$Y^m_{j_1 i_1, j_2 i_2} \leq X^m_{j_1 i_1}, \forall j_1, j_2 \in J, i_1 \in O_{j_1}^{\mathrm{opr}}, i_2 \in O_{j_2}^{\mathrm{opr}}, m \in M \text{ (if } j_1 = j_2, i_2 > i_1), \tag{A7}$$

$$Y^m_{j_1 i_1, j_2 i_2} \leq X^m_{j_2 i_2}, \forall j_1, j_2 \in J, i_1 \in O_{j_1}^{\mathrm{opr}}, i_2 \in O_{j_2}^{\mathrm{opr}}, m \in M \text{ (if } j_1 = j_2, i_2 > i_1), \tag{A8}$$

$$B^m_{j_1 i_1} \leq X^m_{j_1 i_1}, \forall j_1 \in J, i_1 \in O_{j_1}^{\mathrm{opr}}, m \in M, \tag{A9}$$

$$L^m_{j_1 i_1} \leq X^m_{j_1 i_1}, \forall j_1 \in J, i_1 \in O_{j_1}^{\mathrm{opr}}, m \in M, \tag{A10}$$

$$\sum_{m \in M} X^m_{ji} = 1, \forall j \in J, i \in O_j^{\mathrm{opr}}, \tag{A11}$$

$$\sum_{j \in J} \sum_{i \in O_j^{\mathrm{opr}}} U_{ji} \leq N_{\mathrm{A}}, \tag{A12}$$

$$\sum_{j \in J} \sum_{i \in O_j^{\mathrm{opr}}} R_{ji} = \sum_{j \in J} \sum_{i \in O_j^{\mathrm{opr}}} U_{ji}, \tag{A13}$$

$$U_{ji} + \sum_{i_1 \in O_j^{\mathrm{opr}}, i_1 < i} W^k_{ji_1, ji} + \sum_{j_2 \in J \setminus \{j\}} \sum_{i_2 \in O_{j_2}^{\mathrm{opr}}} W^k_{j_2 i_2, ji} = 1, \forall j \in J, i \in O_j^{\mathrm{opr}}, k \in A, \tag{A14}$$

$$R_{ji} + \sum_{i_1 \in O_j^{\mathrm{opr}}, i_1 > i} W^k_{ji_1, ji} + \sum_{j_2 \in J \setminus \{j\}} \sum_{i_2 \in O_{j_2}^{\mathrm{opr}}} W^k_{j_2 i_2, ji} = 1, \forall j \in J, i \in O_j^{\mathrm{opr}}, k \in A, \tag{A15}$$

$$T^{\mathrm{ep}}_{ji} - T^{\mathrm{et}}_{ji} - t^{\mathrm{P}}_{jim} \geq M(X^m_{ji} - 1), \forall j \in J, i \in O_j^{\mathrm{opr}}, m \in M, \tag{A16}$$

$$T^{\mathrm{ep}}_{j_1 i_1} - T^{\mathrm{ep}}_{j_2 i_2} - t^{\mathrm{P}}_{jim} \geq M(Y^m_{j_2 i_2, ji} - 1), i_1 \in O_{j_1}^{\mathrm{opr}}, i_2 \in O_{j_2}^{\mathrm{opr}}, m \in M \text{ (if } j_2 = j_1, i_1 > i_2), \tag{A17}$$

$$T^{\mathrm{et}}_{ji} - T^{\mathrm{ep}}_{j(i-1)} - t_{m'm} \geq M(X^m_{ji} + X^{m'}_{j(i-1)} - 2), \forall j \in J, i \in O_j^{\mathrm{opr}} \setminus \{1\}, m, m' \in M, \tag{A18}$$

$$T^{\mathrm{et}}_{j1} - t_{\mathrm{LU}m} \geq M(X^m_{ji} + U_{j1} - 2), \forall j \in J, m \in M, \tag{A19}$$

$$T^{\mathrm{et}}_{j_1 i_1} - T^{\mathrm{et}}_{j_2 i_2} - t_{m''m'} - t_{m'm} \geq M(W^k_{j_2 i_2, j_1 i_1} + X^m_{j_1 i_1} + X^{m'}_{j_1(i_1-1)} + X^{m''}_{j_2 i_2} - 4), \tag{A20}$$

$$\forall j_1, j_2 \in J, i_1 \in O_{j_1}^{\mathrm{opr}}, i_2 \in O_{j_2}^{\mathrm{opr}} \setminus \{1\}, k \in A, m, m', m'' \in M \text{ (if } j_1 = j_2, i_1 > i_2),$$

$$T^{\mathrm{et}}_{j_1 1} - T^{\mathrm{et}}_{j_1 i_1} - t_{m'\mathrm{LU}} - t_{\mathrm{LU}m} \geq M(W^k_{j_2 i_2, j 1} + X^m_{j_1 1} + X^{m'}_{j_2 i_2} - 3), \tag{A21}$$

$$\forall j_1, j_2 \in J, j_2 \neq j_1, i_2 \in O_{j_2}^{\mathrm{opr}}, m, m' \in M, k \in A$$

$$B^m_{ji}, L^m_{ji}, X^m_{ji} \in \{0, 1\}, \forall j \in J, i \in O_j^{\mathrm{opr}}, m \in M, \tag{A22}$$

$$Y^m_{j_2 i_2, j_1 i_1}, W^k_{j_2 i_2, ji}, U_{j_2 i_2}, R_{j_2 i_2} \in \{0, 1\}, \forall j_1, j_2 \in J, i_1 \in O_{j_1}^{\mathrm{opr}}, i_2 \in O_{j_2}^{\mathrm{opr}}, k \in A, \tag{A23}$$

$$C_{\max}, T^{\mathrm{ep}}_{ji}, T^{\mathrm{et}}_{ji} \geq 0, \forall j \in J, i \in O_j^{\mathrm{opr}}, m \in M, \tag{A24}$$

Model of FJSP_PT

FJSP_PT involves objectives such as makespan, total energy consumption, and workload balance, which can be classified as overall, machine-specific, or vehicle-specific metrics. Over 90% of single-objective studies adopt makespan minimization.

In multiobjective optimization, recent studies increasingly focused on green production, typically combining total energy consumption minimization (Liu et al., 2019; Zhou and Liao, 2020) with efficiency or workload objectives.

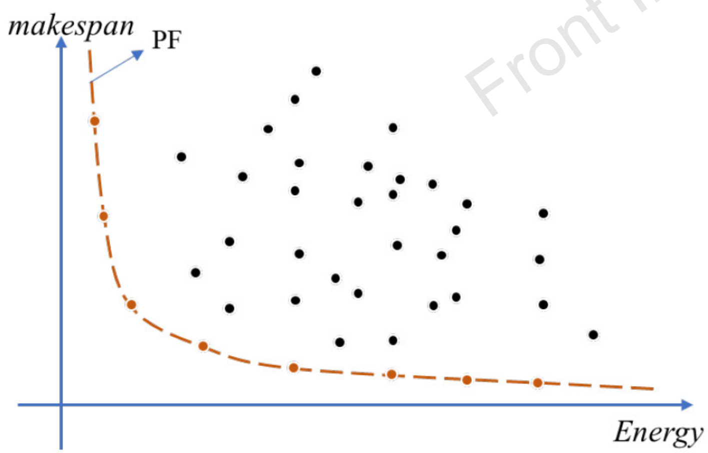


Table 2 Description of objective functions

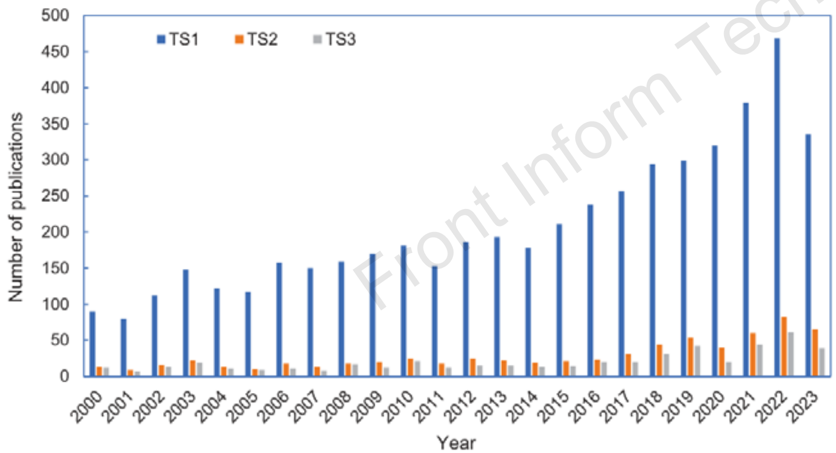
Type	Objective function	Interpretation	Reference(s)
Overall metrics	Makespan	The time when all the jobs have been processed	Bilge and Ulusoy, 1995; Chetto et al., 1995; Ulusoy et al., 1997; Gnanavel Babu et al., 2010
	Mean flow time	The average time that all the jobs spend in FMS	Reddy BSP and Rao, 2006; Anandaraman et al., 2012
	Mean tardiness	The average difference between the completion time and the due date	Subbaiah et al., 2009; Anandaraman et al., 2012; Nageswararao et al., 2014
	Total weighted tardiness or penalty cost	The weighted sum of the difference between the completion time and the due date	Jerald et al., 2006; Poppenborg et al., 2012
	Total energy consumption	The energy consumption of all machines and vehicles	Liu et al., 2019; Wang H et al., 2021; Xin et al., 2023; Xu et al., 2023
	Profit	The ratio of profits from completed jobs within a given time to all jobs	Yung et al., 2009
Machine metrics	Total machine workload	The total working time among all machines	Liu et al., 2013
	Balancing machine workload	The standard deviation of workload among all machines	Sawik, 1996; Hoshino et al., 2008
	Machine utilization	The ratio of total machine down time to total elapsed time	Jerald et al., 2006
Vehicle metrics	Traveling time	The sum of unloading and loading time of all vehicles	Yung et al., 2009
	Distribution cost	The traveling energy-consumption cost and fixed cost of all AGVs used	Zou et al., 2021
	Vehicle utilization rate	The ratio of traveling time to elapsed time	Jerald et al., 2006
	Total waiting time	The sum of waiting time for transportation tasks	Wang XK et al., 2022
	Vehicle energy utilization	The total energy consumed by the vehicles	Yung et al., 2009

Literature review for FJSP_PT

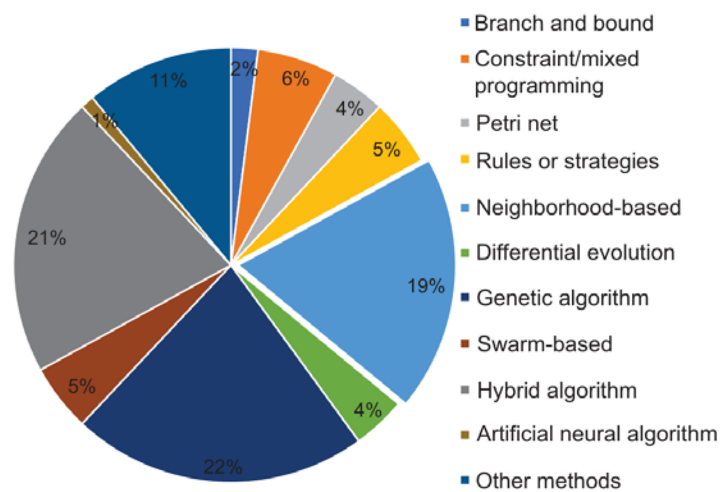
•**Publication trend**: The number of publications on FJSP_PT in FMSs is increasing but remains limited compared to the overall FJSP field.

•**Key journals**: Nearly 100 papers were analyzed, among which about 50% were published in *International Journal of Production Research*, *European Journal of Operational Research*, and *Computer & Industrial Engineering*.

•**Solution methods**: Over 60% of studies use neighborhood-based methods, genetic algorithms, and hybrid algorithms; artificial neural networks are rarely applied.



TS1=((flexible manufacturing system OR flexible job shop) AND scheduling) AND PY=Year
TS2=((flexible manufacturing system OR flexible job shop) AND scheduling AND (AGV OR automated guided vehicle OR handling)) AND PY=Year
TS3=((flexible manufacturing system OR flexible job shop) AND scheduling AND (AGV OR automated guided vehicle OR handling) AND machine) AND PY=Year



Research statuses, trends, and future challenges

Research statuses

- Problem modeling: Excessive assumptions simplify complexity but may alter problem nature; constraints and objectives are oversimplified.
- Solution methods: Most rely on adapting classical FJSP algorithms; lack of deep problem analysis; limited use of AI (e.g., neural networks and reinforcement learning).
- Experimental design: Existing test instances lack parameter diversity; key factors like processing time and energy consumption are insufficiently considered.
- Practical application: FJSP_PT is common in industry but is rarely implemented; real-world applications require integration with data mining and big data.

Research trends

- Small scale to large scale
- Centralized to distributed
- Single objective to multiple objectives
- Certain to uncertain

Future challenges

- Large-scale FJSP_PT
- FJSP_PT with complex constraints
- Dynamic FJSP_PT
- Multiobjective FJSP_PT