Solving Complex FJSP Using a Multi-Agent System with Heuristic

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Abstract

Flexible Job-shop Scheduling Problem (FJSP), which closely represent contemporary manufacturing systems, is regarded as one of the most challenging and crucial scheduling problems. A job-shop scheduling problem that attempts to mimic real-life manufacturing is incomplete without consideration of machine related issues such as setting up and maintenance; and job related issues such as transportation of jobs between machines. Consideration of these factors for FJSP has gained attention in recent times. Majority of the papers, however, deals with only a few of these issues. The proposed work considers the FJSP with maintenance, setup and transportation time, termed as the complex FJSP. This work proposes a multi-agent based approach for solving the complex FJSP.

Keywords
FJSP, transportation time, maintenance, setup, Multi-agent system, simulated annealing

Introduction
The complexity of manufacturing systems is increasing to handle varying customer needs and changing market trends. The scheduling in such complex manufacturing systems is considered to be one of the difficult combinatorial problems. Flexible Job-shop System (FJS), contrary to traditional job shop scheduling, assumes that a machine can perform a variety of operations on the jobs. The scheduling problems related with FJS are called as Flexible Job-shop Scheduling Problems (FJSPs). This problem has attracted a considerable attention from industries and academia due to its closeness to the advanced manufacturing systems. The solution to FJSP needs solving two sub-problems: machine selection and operations sequencing. FJSP was first introduced by Brucker and Schlie (1990). Thereafter, various solution methods have been proposed to solve FJSPs which mainly fall into exact and approximate methods. Exact methods provide optimal solutions but proved to be less efficient due to high computation time. Instead, approximate methods which provide good solutions (not optimal) are mostly methods to solve the FSJPs.

Approximate solution methods generally consist of heuristics and meta-heuristics algorithms. These can be categorized into centralized and decentralized approaches based on the decision-making environment. The solution approach where only single decision-entity takes all decisions is defined as centralized decision-making approach (Ennigrou and Ghédira 2008; Xiong and Fu 2018). While in decentralized approach, multiple decision entities generally solve the scheduling problem. Multi-agent system is widely used decentralized approach for scheduling problems where multiple decision-entities, termed as agents, solve the problem using either cooperative or negotiation based competitive approach.

Since its introduction, attempts have been made to generalize FJSP to consider the real-life scheduling issues. One of the important issues is the maintenance of machines or resources. Maintenance or machine availability issue is quite common in scheduling problems as preventive maintenance is to be scheduled to avoid sudden failure of the machines. Another important consideration is setup time which is needed by machines before processing the jobs. The setup time has been acknowledged where machines need some pre-processing time to make it ready for the processing of the jobs' operations. In addition, the movement of jobs between machines for processing also require time which is called as transportation time. To the best of our knowledge, none of the available research has considered these three issues simultaneously. The proposed work considers these three factors simultaneously for the FJSP and the resulting problem is terms complex FJSP. This work proposes a multi-agent based approach for solving the complex FJSP. The rest of the paper is arranged as follows. Relevant literature is reviewed in section 2. In section 3, the problem statement is provided. The proposed multi-agent based approach is presented in Section 4. Section 5 covers the illustrative and experimental evaluation of the proposed algorithm, which is followed with conclusion in section 6.

2. Literature Review

After being introduced by Brucker and Schlie (1990), the FJSP has started to receive attention of the researchers and industry for finding the various solution approaches. The exact solution approaches, which generally find the optimal solutions, are not practically suitable for large problems such as FJSPs. Therefore, approximate algorithms consisting of different heuristics or metaheuristics have been proposed. Brandimarte (1993) first proposed heuristic based approach where Tabu Search (TS) is used to solve the FJSP followed by various other meta-heuristics i.e. Tabu Search (TS)(Li et al. 2010), Simulated Annealing (SA), Grey Wolf Algorithm (GWO), Genetic Algorithm (GA),)(Kato et al. 2018), Genetic Algorithm (GA)(Kacem et al. 2002a, 2002b; Li and Gao 2016), Particle Swarm Optimization (PSO)(Kato et al. 2018; Singh and Mahapatra 2016), Artificial Bee colony optimization (ABC)(Li et al. 2011; Li, Huang et al. 2020).

It is always emphasized in research to study the scheduling problems which can represent real life scheduling issues along with solution of FJSP where two sub-problems: machine selection and operation sequencing are solved. In literature on FJSP, Maintenance or machine availability issue has received consideration where machines are assumed to be not available for some duration or needed inspection time in industrial practice to avoid the sudden failures (Gao et al. 2006; Li et al. 2013; Wang and Yu 2010). Gao et al. (2006); Li et al. (2013) and Wang and Yu (2010) consider scheduling with flexible maintenance planning in FJSP and solve the problem by hybrid GA, Discrete Artificial bee colony, and Filtered beam search (FBS) algorithm, respectively.

In addition, setup time has also received attention where the job operations are required to perform on multiple machines and the machines require setup time to make them ready before processing the jobs (Mousakhani 2013). The various solution approaches have been proposed to solve the FJSP with setup time. Azzouz et al. (2017); Mousakhani (2013) and Shen et al. (2018) presented an Iterated Local Search (ILS), TS + novel neighborhood search and GA + Variable Neighborhood Search (VNS) to solve FJSP with setup time, respectively. Similarly, transportation time is the time required to move the jobs between machines for processing. It is considered very important when the transfer time consumes considerate amount of time for movement of the jobs between machines and can impact the scheduling decisions (Nouri et al. 2016). Nouri et al. (2016) proposed a holonic multi-agent model where scheduler agent and cluster agents use GA and TS, respectively for the optimization. Chen et al. (2020); Huang and Yang (2019) and Karimi et al. (2017) proposed improved artificial immune algorithm, Imperialist Competitive Algorithm (ICA) and hybrid GA, respectively to solve FJSP with transportation times.

Recently, setup and transportation times are considered simultaneously for FJSP (Li, Deng, et al. 2020; Li and Lei 2021; Sun et al. 2021; Zhang et al. 2020). As per authors' knowledge, no research work has been reported attempting to solve FJSP with maintenance, setup and transportation time simultaneously. This work proposes a multi-agent based solution approach for the Complex FJSP.

3. Problem statement

This section details the mathematical formulation for the complex FJSP. Assuming *N* jobs which are needed to be processed on *M* machines. For complete processing of the job *i*, a set of operations (OP_i) have to be carried out in a predefined sequence. CT_i is the completion time of job *i*. A machine's Preventive Maintenance (PM) must be performed during the defined flexible maintenance interval. Setup time $ST_{ijk,}$ (setup time required for i^{th} job's j^{th} operation on machine k) is required to prepare the machine for processing the next operation. If the subsequent operations are of the same job, the setup time is zero. For processing the first operation of each job, a machine does not need any setup time. $TT_{i,g}^{k}$ is the transportation time to move job i^{th} from machine g to machine k for the next operation. The objective is to minimize the makespan (maximum completion time from all the jobs) (Equation 1) defined as:

$$\text{Minimize } Z = \max(CT_i), 1 \le i \le n \quad (1)$$

4. The proposed approach

This section presents the modified multi-agent based approach proposed by Pal et al. (2023). The next section demonstrates the proposed multi-agent based system.

4.1 The multi-agent based system

The proposed multi-agent based approach uses three agents: the scheduler agent, job agents and machine agents. These are then cooperatively solve the allocation of machine to the jobs' operations along with maintaining the schedule of maintenance. This also checks the inclusion of setup and transportation time. For the optimization, the scheduler agent considers Simulated Annealing (SA) to get the optimal solution.

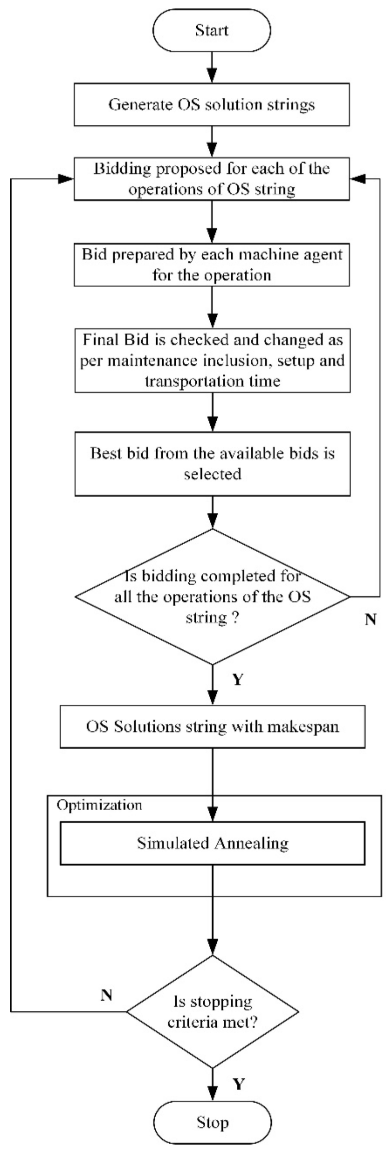

Figure 1. The flow-chart of the multi-agent based system for the complex FJSP

Figure 1 shows the steps to be followed in the proposed multi-agent based model. The scheduler agent initiates the solution process by randomly generating a population of Operation Sequences (OS) strings and sends them to the Job Agent (JA). The OS string consists of job numbers which shows the operation number of the job as per the order of appearance. For the selection of a machine, the bidding process is carried out between the bidder job agent and available machine agents for each operation. The proposed bidding process checks the maintenance planning along with setup and transportation times and the best bid is selected by the job agent. All the operations are allocated to the

best possible machine one by one through bidding and finally, makespan is computed for the string. In order to optimize the allocations, heuristic called Simulated Annealing (SA) is used by the scheduler agent.
SA is based on an algorithmic process where materials are annealed to achieve a state of minimal internal energy value. SA has been often utilized in the optimization process because of its effective local search mechanism for generating near accurate solutions. This work has explored SA in order to achieve optimal solution for complex FJSP. A novel temperature update function of SA based on Hill function was developed by Dai et al. (2019). In this approach, three key modules: the state generation module, acceptance probability and annealing rate are used. The state generation module is used to achieve new OS string with the swap operator (Figure 2) where two position of jobs are randomly swapped.

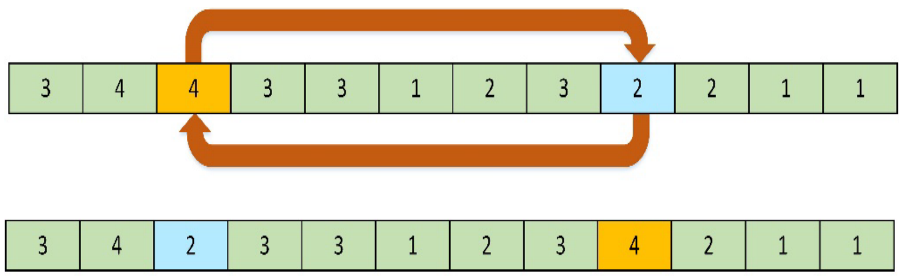

Figure 2. Swap operator (OS vector string)

Acceptance probability module is based on Boltzmann function (Equation 2) where the probability of acceptance when a new state function (new OS string) is higher than the current one.

$$P(i \rightarrow j) = \begin{cases} 1, & Ft(i) \geq Ft(j) \\ \exp\left(\frac{Ft(i)-Ft(j)}{T}\right), & Ft(i) \geq Ft(j) \end{cases} \quad (2)$$

Where *Ft(i)* represents the new state function value (new OS string solution); *Ft(j)* represents the current function value(Original OS string solution); *T* is the current temperature.

Annealing rate module is an important module of SA. A new annealing rate function (Equation 3) based on Hill function proposed by Dai et al. (2019) is used in the proposed SA to avoid premature convergence in the search of optimal solution.

$$T(t) = k \times \frac{T_0^n}{T_0^n + t^n} \quad (3)$$

Where T_0 is a temperature threshold and related with initial temperature; *n* is the hill coefficient.

5. Computational experience

This section reports computational experience by solving three standard test problems taken form literature. For, illustration, however one problem is described in detail. The proposed approach is programmed in python (3.7.7) and processed on an Intel Core processor i5-8250U CPU at 3.6 GHz with an 8 GB RAM. Three problems 4 x 5 (number of jobs x number of machines), 8x8 and 10x10 developed by Kacem et al. (2002a) are considered which were later on modified to include maintenance plan by Karthikeyan et al. (2014), setup and transportation time data by Zhang et al. (2020). The proposed work is the first attempt to solve complex FJSP with consideration of three factors: maintenance, setup and transportation time. The maintenance time and duration, setup time and transportation time data of 4x5 problem for illustration are provided in Table 1, Table 2 and Table 3.

The proposed approach is illustrated for the 4x5 instance developed by Kacem et al. (2002a). The 4x5 instance is modified to include maintenance, setup and transportation time. The proposed approach is applied with initial OS Vector as [3,4,4,3,3,1,2,3,2,2,1,1]. From the sequence of OS string, first number 3 shows job number 3. JA starts bidding for the first operations of job 3 and asks for the bid from all the available machine agents. In response to this ask, each machine agent offers a bid for the operation. This bid evaluates the executable maintenance plan and also handles care the setup and transportation times along with scheduling the operation. From the offered bids, the job agent selects the best bid with minimum completion time. Similarly, for the next job 4, the job agent 4 starts the bid and allocated the machine agent on the basis of best bid. After allocating all the job operations on the machines, final makespan value of 24 is achieved, as shown in the Gantt chart (Figure 3).

Table 1. Processing time of the operations for 4x5 problem

Operation	M_1	M_2	M_3	M_4	M_5
OP_{11}	2	5	4	1	2
OP_{12}	5	4	5	7	5
OP_{13}	4	5	5	4	5
OP_{21}	2	5	4	7	8
OP_{22}	5	6	9	8	5
OP_{23}	4	5	4	54	5
OP_{31}	9	8	6	7	9
OP_{32}	6	4	2	5	4
OP_{33}	2	5	4	2	4
OP_{34}	4	5	2	1	5
OP_{41}	1	5	2	4	12
OP_{42}	5	1	2	1	2
PM_E	0	0	0	1	4
PM_L	3	4	4	4	8
d_k	1	2	2	1	2

Table 2. Setup time table of the 4x5 problem

Operation	M_1	M_2	M_3	M_4	M_5
OP_{11}	1	3	1	1	2
OP_{12}	3	1	2	6	1
OP_{13}	1	4	4	2	2
OP_{21}	2	4	1	5	7
OP_{22}	1	6	7	4	3
OP_{23}	2	3	3	43	4
OP_{31}	4	7	4	3	9
OP_{32}	6	1	2	3	1
OP_{33}	1	5	1	1	2
OP_{34}	4	1	2	1	3
OP_{41}	1	1	1	8	8
OP_{42}	4	1	1	1	1

Table 3. Transportation time table of the 4x5 problem

From	M_1	M_2	M_3	M_4	M_5
M_1	0	4	2	1	5
M_2	1	0	5	1	5
M_3	1	3	0	2	3
M_4	3	1	3	0	1
M_5	4	2	5	3	0

In Figure 3, machines are defined on the ordinate by "M_k", and the time is demonstrated on the horizontal axis. The "green" block defines the setup time, "yellow" for transportation time and "black" block is for maintenance time. The "red double arrow" shows the flexible maintenance duration during which maintenance should be started. The other color blocks define the processing of the job operations.

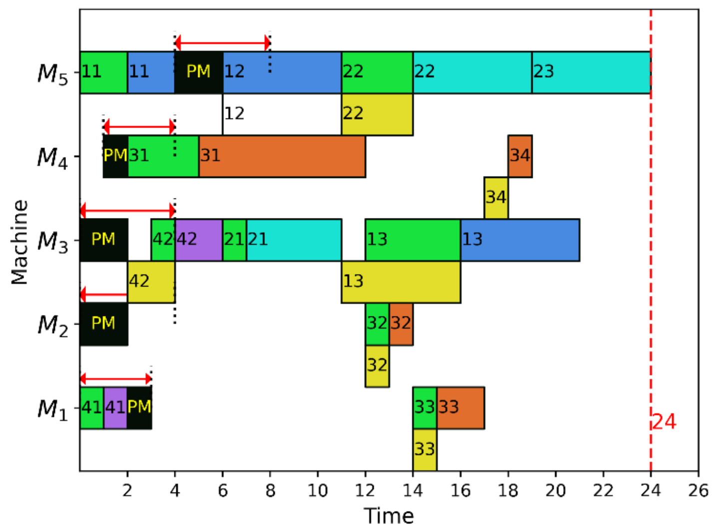

Figure 3. The Gantt chart for the illustrative example

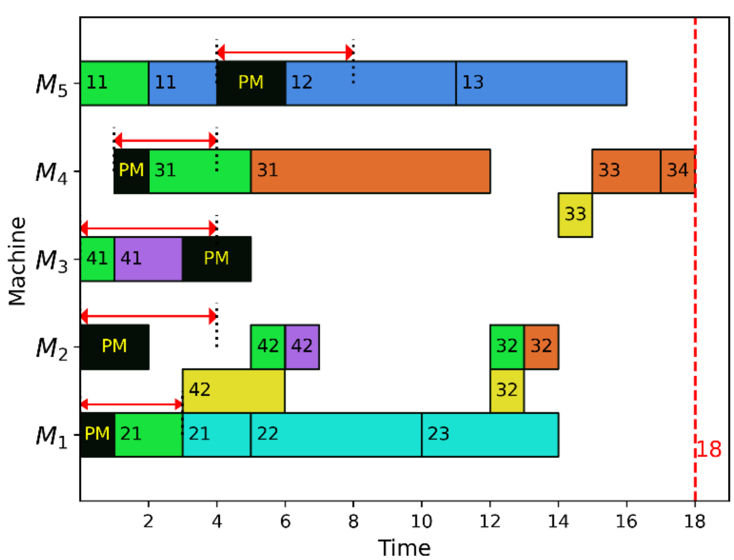

Figure 4. The optimal Gantt chart for the 4x5 problem

From the experimental observations, the population size of OS strings is taken as 50 and similarly, the number of iterations to be carried out is also fixed to 50. The run of each problem instance is carried out ten times to get the best makespan. For optimization, SA is implemented. The best makespan of three problem instances are generated using the proposed approach. Table 4 shows the comparison of results with three state of the art solution approaches: FJSP with maintenance planning only by Rajkumar et al. (2010), FJSP with setup and transportation time only (Pal et al. 2023; Zhang et al. 2020). The Gantt chart for the best makespan for 4x5 problem instance is shown in Figure 4. The proposed approach which has considered three factors though the results of makespan are competitive and effective. Thus, the proposed approach has been found to be promising approach to solve the complex FJSP.

Table 4. Comparison of the results for the different cases of FJSP

Instance Problem	GRASP (Rajkumar et al. 2010)	IGA (Zhang et al. 2020)	MAS + hGWO (Pal et al. 2023)	Our approach
	Makespan (FJSP with maintenance planning only)	Makespan (FJSP with setup and transportation time only)	Makespan (FJSP with setup and transportation time only)	Makespan (FJSP with three factors: maintenance, setup and transportation time)
4x5	16	18	16	18
8x8	18	31	23	32
10x10	9	17	11	15

6. Conclusion

Flexible job shop scheduling problem (FJSP) has considered important and difficult scheduling problems. Its closeness to the modern manufacturing systems is the reason for its wide attention from the academia and industries. Nowadays, consideration of real life issues of the scheduling problems have been started to develop the solution approach which can target and solve the actual and complex scheduling problems. For real scheduling problems, factors such as maintenance, setup and transportation times are generally assumed. But, existing research papers have majorly counted these factors individually for the FJSP. The proposed work has considered these issues: maintenance planning, setup and transportation times simultaneously and termed it as complex FJSP. For the solution, a multi agent based approach is proposed. An example of 4x5 problem instance is solved and illustrated in detailed. For the experimental comparison, three problems 4x5, 8x8 and 10x10 are solve solved and compared. The proposed approach is the first approach to be developed for the FJSP with three factors so it has been compared with FJSP with individual factors. The comparison has proved the effectiveness of the solution approach. The Gantt chart with optimal solution for 4x5 problem is demonstrated. In future, the proposed approach is going to be further improved with hybrid algorithms and by solving more number of problems.

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