IEEE Access
Multidisciplinary ⁝ Rapid Review ⁝ Open Access Journal

Received November 25, 2020, accepted December 8, 2020, date of publication December 10, 2020,
date of current version December 30, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.3043880

Performance Assessment of Dynamic Flexible Assembly Job Shop Control Methods

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This work was supported in part by the National Natural Science Foundation, China under Grant 51975129, Grant 71572049, and Grant 61973089, and in part by the Guangdong Provincial Natural Science Foundation, China under Grant 2019A1515012158.

ABSTRACT Developments of information technology provide a foundation for implementing shop floor control in high variety production environments. A dynamic flexible assembly job shop is abstracted from a mold industry, we suggest the use of a hierarchical production control framework – dynamic flexible assembly job shop control (DFAJSC). DFAJSC consists of three sub-decisions, which are release decision, routing decision and sequencing decision, these decisions are made dynamically to react to disturbances (e.g. machine breakdown, rush order). As no study has applied controlled release in flexible assembly job shop, we would improve state-of-the-art controlled release methods for flexible assembly job shop. Building on this, we explore when and how routing decision is incorporated. Simulation experiments are designed to examine the performances of DFAJSC methods, coupling effects of our improved controlled release methods and routing decision rules are evaluated in different levels of disturbances. Results reveal that input/output control (IOC) release methods are overall best performed in all levels of disturbances, Dynamic Process Planning (DPP) decision is not significantly advantageous over Non-Linear Process Planning (NLPP) decision combined with IOC release methods. Thereof, IOC release integrated with NLPP is suggested for practical applicability.

INDEX TERMS Flexible assembly job shop, dynamic scheduling, shop floor control, controlled release, simulation.

I. INTRODUCTION

Assembly job shop (AJS) is an extension of job shop (JS) with the consideration of jobs' assembly relations. A job is not completed even if it finishes all operations, it has to be assembled into final products after the completion of its related jobs. AJS and JS share a similarity that an operation is only performed at one specific machine. Unique resource constraint forces jobs to compete for certain resources, it further restricts the progress of some products close to completion. The emergency of flexible manufacturing system (FMS) relaxes the resource constraint for AJS. In the manufacturing of tier mold, the cavity can be processed with alternative process plans (e.g. electric discharge machining or high speed milling), which is categorized as process flexibility by [1]; Besides, some operations within a process plan can be performed on more than one machine, which is categorized as operation flexibility. FMS facilitates the synchronization of related parts, it also complexes the production planning and control for AJS. AJS with process and operation flexibility is termed as flexible assembly job shop (FAJS) by [2].

Considerable efforts have been spent in the domain for flexible job shop scheduling problem (FJSP) [3]–[10], which is also known as Integrated process planning and scheduling. As a generalization of FJSP, prior studies on flexible assembly job shop scheduling problem focus on the determinant production environment. Reference [2] constructs a mathematical model of flexible assembly job shop scheduling. Building on this, search-based algorithms are used to generate an explicit schedule for small and medium sized instances [11]. In dynamic production environments with disturbance (e.g. machine breakdown, reworks, urgent orders, etc.), rescheduling strategies are used to revise former generated schedule. The scheduling/rescheduling framework is known as predictive reactive scheduling by [12]. Predictive reactive scheduling has been theoretically applied in dynamic

The associate editor coordinating the review of this manuscript and approving it for publication was Giambattista Gruosso.

flexible assembly job shop (DFAJS) by [13]. Relative works consider small sized instances with low-level disturbance, DFAJS abstracted from high-variety environment is characterized by large-scale instances and frequent disturbances. Thereof, weaknesses of predictive reactive scheduling are apparent: 1) large-scale instances bring about an explosion of solution space, and even result in a dimensional disaster; 2) it is difficult for rescheduling to deal with frequent disturbances, and frequent rescheduling may increase the nervousness of shop floor management; 3) explicit schedule requires expensive software purchase to ensure timely and effective results. A generic control method coupling genetic algorithm with distributed arrival-time control is proposed to optimize the Just-in-Time (JIT) objectives for dynamic flexible job shop scheduling [14]. The results of [14] verify the effectiveness of controlling the entry time of new arriving jobs, which is a technique used in shop floor control.

Shop floor control (SFC) is a hierarchical production control technique, it integrates a centralized controlled release with distributed sequencing decision in front of workstations [15]–[18]. Controlled release is acknowledged as a powerful control instrument in the framework of shop floor control [19]–[26]. The release of new arriving jobs is regulated to stabilize the throughput time on the shop floor, unprioritized jobs are kept in a pre-shop pool, in turn the shop floor is shielded from external disturbances. As decisions are made depending on real-time data from production process, SFC has rapid reactivity towards disturbance. SFC has been used in various production environments: relative works in assembly job shop reveal that incorporating controlled release can further improve shop performance [27]–[29]; Relative studies in flexible job shop show that routing decision has an impact on the performance of SFC methods [30]–[33].

As a core decision in SFC, existing controlled release methods can be categorized into time phased controlled release and input/output controlled (IOC) release by [34]. Reference [27] suggests that load-based release, a special form of IOC release, outperforms time phased release in AJS. To the best of our knowledge, no study has been concerned about the application of controlled release in DFAJS. Thus, we address the first question:

- which controlled release method can improve overall performances of SFC in DFAJS?

Dynamic flexible assembly job shop control (DFAJSC) consists of release decision, routing decision and sequencing decision. Their coupling effects require to be evaluated in different disturbance levels in order to testify their applicability in practice. Hence, our second question is:

- how do DFAJSC methods behave in different disturbance environments?

Another contribution of this work is the investigation of the timing of routing decision. Reference [31] suggests routing decision at release stage can ensure balanced workloads, while combining routing decision with dispatching can react to disturbances. In respect of this, our third question is addressed as follows:

- when and how routing decision should be embedded in DFAJSC?

The remainders of this paper are organized as follows: Section II presents the background of our research; improved DFAJSC methods are outlined in Section III; Section IV presents the simulation and the experiment designs of this study; The results are presented and discussed in Section V; Finally, Section VI concludes our work and discusses the future work.

II. THEORETICAL BACKGROUND

A. DYNAMIC FLEXIBLE ASSEMBLY JOB SHOP

New product arrives at the shop consistently, the information (e.g. number of parts, process routes of each part) is not known until its arrival. The parts or subassemblies belonged to one product are uniformly called as jobs in the rest of this paper. Fig.1(a) presents the assembly relation of a product, and an example of job j's process route network is presented in Fig.1(b).

Each node in the network model of a process plan represents an operation/machine pair, it includes alternative machines as well as their processing times to perform an operation. The network given in Fig.1(b) contains two OR relations, OR relation is used to represent precedent operation with alternative operation/machine pairs. Two types of flexibility are considered in Fig.1: the first type is process flexibility: a job is able to be processed by alternative process routes, Fig.1(c) shows all possible process routes expanded from the network presented in Fig.1(b); the second type is the operation flexibility: an operation could be processed in alternative machines. The assembly operation of a product cannot commence until all its belonging jobs are finished.

B. SCHEDULING VS SHOP FLOOR CONTROL

In this subsection, we would compare two alternative approaches, which are flexible assembly job shop scheduling (FAJSS) and dynamic flexible assembly job shop control (DFAJSC). Their concepts are presented in Fig.2. Before constructing the specific mathematical formulations, declarations of sets and indices are defined as follows.

Sets and indices

t_0: current decision point

i: unfinished products ($i \in I$), $|I|$ is the number of unfinished products

j: unfinished jobs ($j \in J$), it includes work-in-process and unreleased jobs ($J = J_w \cup J_u$)

J_i: jobs belonged to product i, $|J_i|$ is the number of related jobs in product i

p: process routes of job j $\left(p \in P_{ij}\right)$, P_{ij} denotes set of process routes for job j

O_{ijp}: Ordered set of operations in process route p of job j

k: kth operation of process route p $\left(k \in O_{ijp}\right)$, $k(o)$ and $k(f)$ denote the first and final operation

m: Machines ($m \in M$)

M_{ijpk}: Sets of alternative machines for operation k $\left(M_{ijpk} \subseteq M\right)$

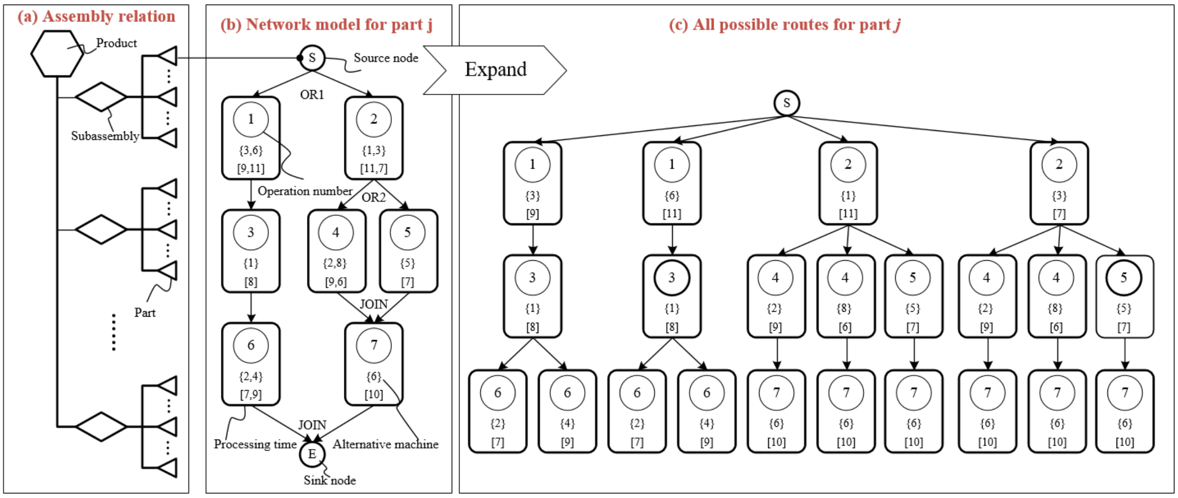


FIGURE 1. Assembly product and network of process routes.

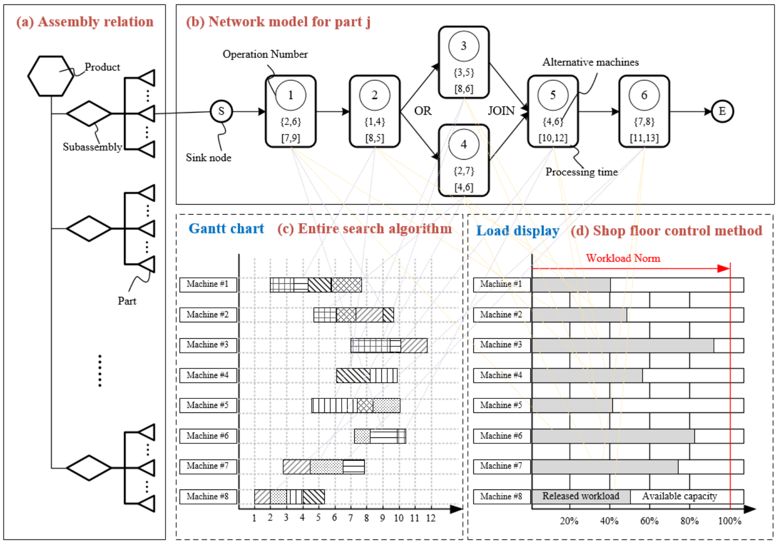


FIGURE 2. Concepts of flexible assembly job shop scheduling and control.

Pt_{ijpk}^{m}: processing time of operation k on machine m

aot_i: assembly operation time of product i

AT_i: arriving time of product i

D_i: due date of product i

A_m: workloads of machine m before release

W_m: workloads of machine m after release

N_m: workload level of machine m

L: large number;

Decision variable

$w_{ijp} = 1$ if process route p of job j is selected and 0 otherwise

$x_{ijpk}^{m} = 1$ if machine m is selected for operation k and 0 otherwise

$y_{ijpi'j'p'}^{m} = 1$ if operation k of job j precedes operation k' of job j' on machine m and 0 otherwise

S_{ijpk}^{m}: Start time of operation k on machine m

C_{ijpk}^{m}: Completion time of operation k on machine m

C_i: Completion time of product i

C_{ij}: Completion time of job j ($j \in J_i$)

$X_j = 1$ if job j is selected for release and 0 otherwise

$X_{jp} = 1$ if process route p is selected for released job j and 0 otherwise

$X_{jpk}^{m} = 1$ if machine m is selected for operation k and 0 otherwise

FAJSS model is complex, the objectives of scheduling in flexible assembly job shop are a series performance measures concerned with the completion time of each jobs. More specifically, they are listed as follows:

- Mean flow time:

$$f_1\left(C_1, C_2 \ldots C_{|I|}\right) = \sum_{i \in I} (C_i - AT_i) / |I|$$

- Mean tardiness:

$$f_2\left(C_1, C_2 \ldots C_{|I|}\right) = \sum_{i \in I} \max\{0, C_i - D_i\} / |I|$$

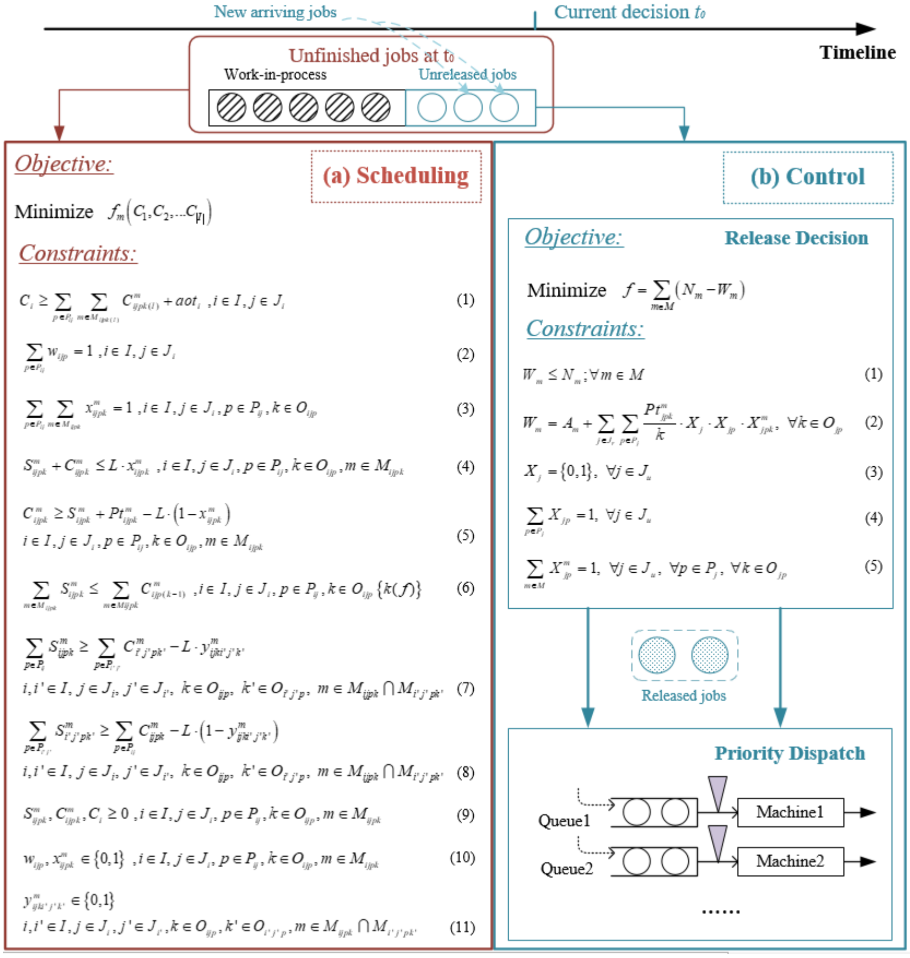


FIGURE 3. Mathematical model of flexible assembly job shop scheduling and control.

- Percentage of tardy products:

$$f_3\left(C_1, C_2 \dots C_{|I|}\right) = \sum_{i \in I} \phi\left(C_i - D_i\right) / \left|I\right|,$$

where $\phi(a) = 1$, if a > 0 and 0 otherwise

FAJSS is to decide start and finish time of each operation on its alternative machines at t_0 as showed in Fig.3 (a). FAJSS includes scheduling of WIP's unfinished operations as well as new arriving jobs' operations. Constraint 1 defines the completion time of a product, i.e. completion time of the latest finished operation of product i's belonged part plus the assembly time. Constraint 2 represents that only one process route must be selected for each job. Constraint 3 guarantees that each operation of a job is assigned to one machine within the selected process route. Constraints 4 and 5 specifies the start and completion time of each operation. Constraint 6 ensures that precedence relation between operations is not violated. Constraints 7 and 8 ensure that two distinctive jobs cannot be simultaneously processed in one machine. Finally, the conditions on the decision variables are presented in constraints 9-11. Optimal solution can be obtained by [2] in small sized instances. A novel constraint programming method is applied by [13] to improve the computational efficiency to search optimal solution, it is still impractical for larger sized instances with frequent disturbances. Hence, meta-heuristic is used to improve search efficiency of solutions. Particle swarm optimization algorithm is proposed by [11] to solve a medium size instance. A job constraint genetic algorithm is presented by [35] for FAJSS to minimize the makespan. Reference [36] takes makespan, total tardiness and total workload as optimizing objectives, a distributed ant colony system is proposed to explore the pareto front of FAJSS. Nevertheless, excessive computation time makes meta-heuristic algorithms not adjustable for practical production.

Contrarily, DFAJSC is decomposed into multi-level decisions, where controlled release is the core decision. Controlled release decision focuses on unreleased jobs, which includes the remaining jobs at last decision point and new arriving jobs. An integer linear programming (ILP) model of release decision is presented by [37] in job shop, and jobs are released as long as they will not violate the upper bound of resources within their selected process routes. We extend this ILP model in DFAJS, routing decision is incorporated into release decision. Released jobs and their process routes are determined by the release decision model in Fig.3 (b): the objective is to make the workloads close to the upper bound. Constraint 1 protects workstation's workloads from exceeding upper bound, the workloads include the workloads of released jobs and the unfinished workloads of workstation before release by constraint 2. The workloads of released jobs are calculated based on the corrected aggregate approaches proposed by [38]. Constraint 3 represents that the release decision of job is 0-1 variable, and constraints 4-5 confine that only one process route can be chosen and each operation can only be performed by one specific machine. After released jobs reaches workstations, they are sequenced by priority dispatching rules and wait to be processed.

Routing decision (process planning task) in dynamic flexible assembly job shop can be either made dynamically by Distributed Process Planning (DPP) or made fully static by Non-Linear Process Planning (NLPP) [2]. DPP is used by [5] in dynamic flexible job shop, while only immediate release is taken into consideration. Reference [31] compares these two routing decision approaches under controlled release. DPP is found to be respond quickly to disturbances, and NLPP can lead to balanced workloads across workstations. Later, [32] suggests DPP cannot totally outperform NLPP in case of limited workloads and low degree of machine interchangeability. As for the routing decision rules, [39] incorporates NLPP in periodic release, and investigates the coupling effects of nine routing decision rules (e.g. processing time-based rules and workload-based rules) in FJSP, the results reveal that processing time-based routing decision rules outperform workload-based rules.

Dispatching rule is one of the widely used approaches for sequencing decision, and readers are referred to related works [5], [40]–[46]. Designing a sophisticated rule is a trial and error process, and evolving composite rules using genetic algorithm have become a new potential solution in dynamic FJSP [47]–[51]. Cooperative coevolution has been embedded in Genetic programming (GP) to evolve routing and dispatching rules [47], [51], and automatically designed rules are suggested to achieve better performances than manual designed rules in dynamic FJSP. Nondominated sorting genetic algorithm-II (NSGA-II) is incorporate into GP to solve multi-objective dynamic FJSP [47], [48], [51], [52]. It is suggested that the functions of automatically designed rules have great concerns with the choice of job and shop features [49], [53], [54]. Therefore, it is still important to investigate the behaviors of manual designed rules in DFAJSP under different production environments, as it can provide a theoretical foundation for the selection of features in GP.

The following section concentrates on literature concerned with controlled release methods used in AJSP [27], [28], [55]–[57] and FJSP [30]–[32], [39].

C. CLASSIFICATION OF CONTROLLED RELEASE

An important criterion to distinguish between controlled release methods is release mechanism, and existing controlled release methods can be classified into two categories in Fig.4. The first type is time phased release, a job is released when its planned release date (PRD) is reached. The second type is based on the input/output control (IOC) principle proposed by [58]. WIP is regulated in a critical value based on the output feedback information, the task of shop floor management is simplified without reduction in output. Load-based controlled release is a special form of IOC method, as the WIP are controlled by limiting workloads in the shop floor, it has been applied in assembly job shop.

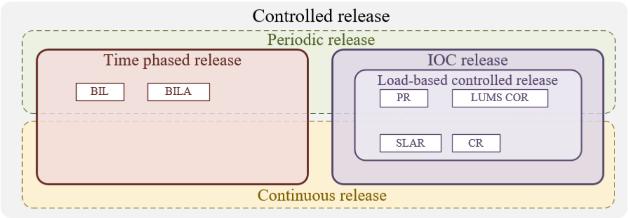


FIGURE 4. **Classification of controlled release methods.**

1) TIME PHASED RELEASE METHODS

Backward infinite loading (BIL) belongs to time phased category, it is firstly employed in AJSP by [56]. On the basis of BIL, [27] proposes Backward infinite loading for assembly job shop (BILA) by including a completion delay in the calculation of PRD. Simulation experiments conducted by [27] reveal that BILA inherits the function of BIL and slightly enhances delivery performance.

Time phased methods focus on the timing function by releasing jobs in time, and the progress of related parts is ensured in this way. Time phased methods are sensitive to the operation flow time allowance suggested by [56], operation flow time is frequently interfered by fluctuated shop floor workloads as well as disturbances in dynamic production environments. Thereof, performance of time phased controlled release needs to be evaluated in DFAJS.

2) IOC RELEASE METHODS

Load-based IOC release is a widely acknowledged approach for high variety production environments. A criterion to distinguish between load-based IOC release methods is whether release occurs at fixed intervals or triggered by certain events. The former type is periodic release, and it is first used in assembly job shop by [55], but it lacks comparison with immediate release. The second type usually combines several continuous triggers, [28] investigates the effects of periodic and continuous release in AJSP, simulation experiment results show that a continuous release method - superfluous load avoidance release (SLAR) proposed by [59] is best performed at percentage tardy in all scenarios.

IOC release combines a timing function with a balancing function. Workloads are regulated and balanced by setting workload upper bound for each workstation, and the balanced workloads in turn enhance the stability of operation flow time. Balancing function not only facilitates the timing function by improving the accuracy of PRD, but also protects

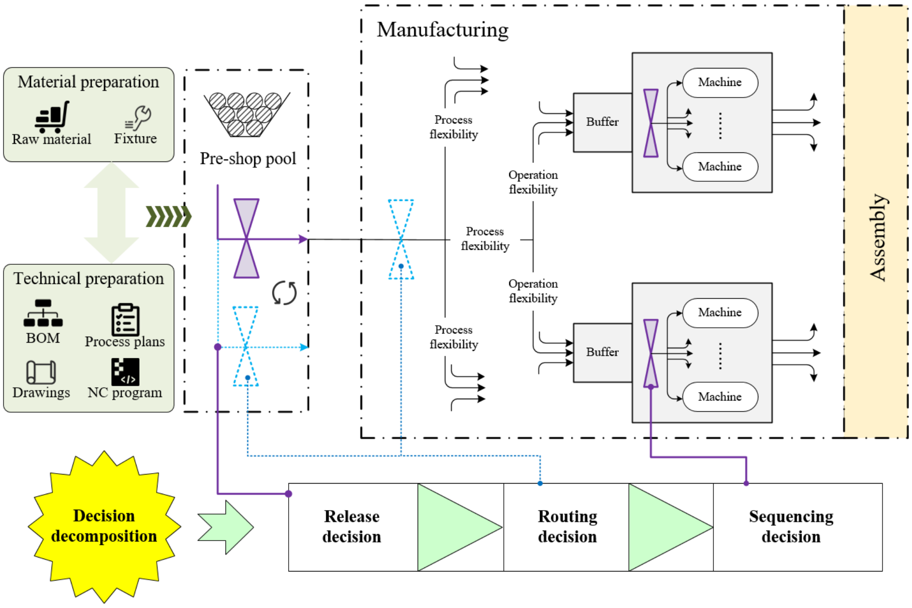


FIGURE 5. Hierarchical framework of dynamic flexible assembly job shop control.

the shop floor against disturbances. Timing and balancing function of IOC methods together contribute to a predictable completion of related parts. Prior studies have shown that IOC release has the potential to outperform time phased release in AJSP [27], [28]. However, balancing function of IOC release is criticized to prevent some urgent but large parts from released on time. Hence, IOC release needs further evaluation in DFAJS.

III. DYNAMIC FLEXIBLE ASSEMBLY JOB SHOP CONTROL METHODS

DFAJSC can be decomposed into three sub-decisions, as presented in Fig.5. As no study has investigated controlled release methods in flexible assembly job shop, to answer the first question of our research, existing controlled release methods have to be improved to be adjusted in DFAJS. Controlled release methods and priority rules are presented and improved in the remaining part of this section.

A. CONTROLLED RELEASE METHODS

According to the categories in the literature review, we would improve a time phased release method and three IOC release methods to make them adjustable in DFAJS. The improvements focus on two aspects in release decision procedure, including the process routes priority calculation and pool sequencing rule.

1) BACKWARD INFINITE LOADING METHOD

BIL is a typical time phased release method triggered at fixed time interval, it takes planned release date (PRD) as pool sequencing rules, jobs with their PRDs falls within the next release period are released. As the original BIL calculate the PRD by infinite backward scheduling from the due date within a determined routing, BIL for flexible assembly job shop is improved by taking the mean value of each route's PRD by backward scheduling from the due date. The pseudo code of improved BIL is given below.

Method: BIL

```
Input: A set of unreleased jobs set $J_u$
Output: A set of jobs $J_r$ released to shop floor
Sort the unreleased jobs by pool sequencing rules
Foreach job $j$ in $J_u$ do:
  Prioritize process routes of job $j$ according to certain rules
  If PRD of job $j$ falls within the next release period then
    Job $j \rightarrow J_r$;
  else
    job $j$ remains until next decision
```

2) PERIODIC RELEASE METHOD

PR is a typical load-based IOC release method, jobs are reviewed and released at periodic time intervals. Periodic release applies an upper bound to limit the workloads of each workstation within a desirable level. In flexible assembly job shop, routing decision is incorporated into release decision. Given all process routes of a job and shop status at release decision point, and a job cannot fit in the upper bound of one workstation within the highest prioritized process route. There are two alternatives to tackle with this situation: 1) The job always prefers the highest prioritized process routs, even if it has to remain in the pre-shop pool and waits for the next release decision; 2) A less prioritized process route is chosen for a job to ensure its timely release. Therefore, two versions of PR are proposed: the first version favoring highest prioritized process route is named as PR-I, while the second is called PR-II. The pseudo codes of two improved periodic release are presented as follows.

Method: Periodic Release Version I (PR-I)

```
Input: A set of unreleased jobs set $J_u$, workloads of each workstation
Output: A set of jobs $J_r$ released to shop floor
Sort the unreleased jobs by pool sequencing rules
Foreach job $j$ in $J_u$ do:
    Prioritize process routes of job $j$ according to certain rules
    The route with highest priority is $p'$
    Foreach operation $k$ in $O_{jp'}$ do:
        If $W_m \leq A_m + \frac{Pt^m_{jp'k}}{k}$ then
            $flag$ := false
            Break
    Job $j \rightarrow J_r$ if $flag$=true else remain in the pool
```

Method: Periodic Release Version II (PR-II)

```
Input: A set of unreleased jobs set $J_u$, workloads of each workstation
Output: A set of jobs $J_r$ released to shop floor
Sort the unreleased jobs by pool sequencing rules
Foreach job $j$ in $J_u$ do:
    Prioritize process routes of job j according to certain rules
    Foreach route $p$ in $P_j$ do:
        Foreach operation $k$ in $O_{jp'}$ do:
            If $W_m \leq A_m + \frac{Pt^m_{jp'k}}{k}$ then
                $flag$ := false
                Break
    Process route $p$ is selected for $j$ if $flag$=true
    Job $j \rightarrow J_r$ if $flag$=true else remain in the pool
```

3) PERIODIC RELEASE WITH STARVATION AVOIDANCE METHOD

PRSA combines the periodic release with a continuous release trigger known as the starvation avoidance (SA) mechanism. Original periodic release method employs the upper bound, which may introduce premature workstation idleness. Besides, it suffers from a weakness that it cannot react to the depletion of buffer in the release interval, and starvation avoidance can quickly replenish the direct load of the starving workstation by releasing a job from the pool. The periodic element of PRSA is exactly the same as PR, while the routing decision strategy of SA mechanism follows the periodic elements. To avoid duplication, here we show the procedure of improved SA mechanism as follows. As SA mechanism also facilitates the release of some urgent jobs rejected for violating workload level, and we also adopt the PRD as pool sequencing rule. The pseudo codes of SA mechanisms for PRSA-I and PRSA-II are presented as follows.

Mechanism: Starvation Avoidance of PRSA-I

```
Input: A set of unreleased jobs set $J_u$, a starving workstation $w'$
Output: job $j$ pulled to starving workstation $w'$
Sort the unreleased jobs by certain pool sequencing rule
Foreach job $j$ in $J_u$ do:
    Prioritize process routes of job j according to certain rules
    The route with highest priority is $p'$
    If $w' \in M_{jp'k(o)}$ then
        Job $j$ is pull to workstation $w'$ and $p'$ is selected
        Break
```

Mechanism: Starvation Avoidance of PRSA-II

```
Input: A set of unreleased jobs set $J_u$, a starving workstation $w'$
Output: job $j$ pulled to workstation $w'$
Sort the unreleased jobs by certain pool sequencing rule
Foreach job $j$ in $J_u$ do:
    Prioritize process routes of job $j$ according to certain rules
    Foreach route p in $P_j$ do:
        If $w' \in M_{jpk(o)}$ then
            Job $j$ is pulled to workstation $w'$ and $p$ is selected
            Break
```

4) SUPERFLUOUS LOAD AVOIDANCE RELEASE METHOD

SLAR is a pure pull type release mechanism, it consists of two continuous triggers. The first continuous trigger is the starvation avoidance mechanism, which pull a job from the pool whenever a workstation is starving. The second is an urgent continuous trigger, and it pulls urgent jobs from the pool when there are no urgent jobs in the queue of a workstation. Instead of controlling the queue length of workstation as PR, SLAR replenishes direct load in workstations by frequent examination of job's urgency and workstation's starvation. The improved procedure of SLAR in DFAJSC is focused on the calculation of PRD and PST. To ensure the timely release of job, iteration is used to find a feasible route for the job with highest priority.

Mechanism: Urgent Continuous Trigger for SLAR

```
Input: A set of unreleased jobs set $J_u$, a workstation $w'$ with no urgent job
Output: job $j$ pulled to workstation $w'$
Sort the unreleased jobs by certain pool sequencing rules
Foreach job $j$ in $J_u$ do:
    If PRD of job $j$ has passed then
        Prioritize process routes of job $j$ according to certain rules
        Foreach route p in $P_j$ do:
            If $w' \in M_{jpk(o)}$ then
                Job $j$ is pulled to workstation $w'$ and $p$ is selected
                    Break
```

B. ROUTING DECISION RULES

Two types of routing decision rules are used to incorporate with controlled release, the first type is concerned with the processing time, while the second is concerned with the workloads of available resources. The processing time-based rules include Smallest processing time and Smallest total processing time, and workload-based rules include Smallest workloads and Smallest mean workloads. These four rules are selected as they outperform other rules in flexible job shop scheduling [5]. Additionally, Random selection is also used, and these five rules are described as below:

- Random selection (RS): The process route of a job is randomly selected from all process routes, routing decision is made by NLPP approach. We focus on the coupling effects of controlled release and routing decision rule, thus a weak rule is required to be used as a baseline comparison.
- Smallest Processing time (SP): Routing decisions are made by DPP approach. The machine with smallest processing time of an operation node is selected, unselected operation nodes are disposed. i.e. select an available machine that satisfies the following condition:

$$p^* = \arg \min_{m \in M_{ij}} \left\{ Pt_{ijpk}^{m} \right\} \tag{1}$$

- Shortest total processing time (STPT): Routing decisions are made by NLPP approach, the process route with the shortest total processing time is selected. i.e. the process route that satisfies the following condition is selected:

$$p^* = \arg \min_{p \in P_{ij}} \left\{ \sum_{k=1}^{h} Pt_{ijpk} \right\} \tag{2}$$

- Smallest workloads (SW): Routing decisions are made by DPP approach. Similar to SP rule, the machine with smallest workloads is selected. i.e. select an available machine that satisfies the following condition:

$$p^* = \arg \min_{m \in M_{ij}} \{WN_{km}\} \tag{3}$$

- Smallest mean workloads (SMW): SMW has both NLPP and DPP versions. NLPP version of SMW rule selects the process route with the smallest mean workloads before a job is released. DPP version of SMW rule selects the next machine with the smallest mean workloads of all unfinished operations, the unselected operation nodes are disposed. i.e. the process route that satisfies the following condition is selected:

$$p^* = \arg \min_{p \in P_{ij}} \left\{ \sum_{k=1}^{h} (WN_{km} - WL_{km})/h \right\} \tag{4}$$

C. SEQUENCING DECISION RULES

As stated above, unreleased jobs are sequenced by an improved PRD pool sequencing rule, a small modification of PRD is made in formulation 5. The average PRD of all process routes is used as the job's PRD, job with smaller PRD is given higher priority to release decision.

$$PRD_{ij} = \frac{\sum_{p \in P_{ij}} \left(DD_i - \left| O_{ijp} \right| \times \beta \right)}{\left| P_{ij} \right|}, \quad \forall i \in I, \ \forall j \in J_i \tag{5}$$

In order to interact with the timing function of controlled release method, our research employs a Planning Start Time (PST) dispatching rule. PST is reported to function well with controlled release methods by [59] and [28]. The job with the earliest PST is selected, the PST is obtained by due date minus the number of unfinished operations multiplied by a slack factor β. Here we set the slack factor β to 4 units in all experiments to achieve the best performance, and the slack parameter in the calculation of PRD is the same as β. The equation is as follows, Where UO_{ijp} is the set of unfinished operations of job $j's$ selected process route.

$$PST_{ijpk} = DD_i - \left| UO_{ijp} \right| \times \beta, \quad \forall i \in I, \ \forall j \in J_i, \ \forall p \in P_{ij} \tag{6}$$

IV. SIMULATION

To reveal the effectiveness of DFAJSC methods, we first abstract a simulation model of flexible assembly job shop from a real production case in subsection A. Shop performance measures and experiments are designed in subsection B to give a good insight of the improved methods.

A. SHOP CONFIGURATION & JOB CHARACTERISTICS

Our simulation model is abstracted from a tier mold manufacturer, we focus on the production of the cavity of a tier mold. A cavity is made up of several subassemblies (e.g. thread ring and sidewall), sidewall is also composed of several parts. The production of tier mold cavity is characterized by its long manufacturing cycle, which is much longer than its assembly stage. The assembly operation time is negligible under this circumstance, and the assembly structure of a product can be simplified as flat structure, i.e. a product is directly assembled from several parts or subassemblies. We capture the uncertainty in assembly product level by setting the number of parts uniformly distributed from 2 to 6.

Process and operation flexibility are common in the manufacturing of tier mold's cavity. For instance, the thread ring can be either processed by electric discharge machining or high-speed milling, this is categorized as process flexibility. The carving operation can be performed in alternative machines, and this is categorized as operation flexibility. We capture the uncertainty in process routes by randomly generating process route network from the five network models presented in Fig.6, the presented network models represent the typical process plans in the cavity manufacturing of tier mold. The number of alternative process plans within a network is discrete uniformly from 3 to 4, and each process plan contains 3 to 5 operations. As for operation flexibility, the number of alternative machines that can perform one operation is discrete uniformly from 1 to 3. We also extend

TABLE 1. Overall features of simulation models.

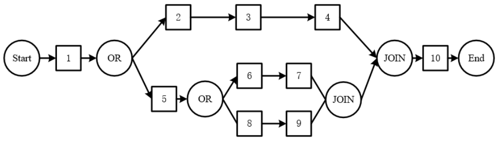
Shop	Routing variability	Random routing with re-entrant flows
	No. of workstations	Eight
	Workstation capacities	All equal and constant over time
	Shop average utilization	90% at scenario without disturbance
Product	Assembly structures	No. of parts is discrete uniform U [2,6]
	Due dates	Arrive time plus allowance following U [30,60]
	Inter-arrival times	Exponential distribution
Job	Network of process routes	Randomly matches Fig 6
	No. of alternative machines per operation	Discrete uniform U [1,3]
	Operation processing times	Uniform U [0.8,1.2]

the uncertainty in the processing time in alternative machines, the processing times are generated from uniform distribution U [0.8, 1.2]. The difference between longest and shortest processing time does not exceed 50%, this coincides with the processing time setting with [13].

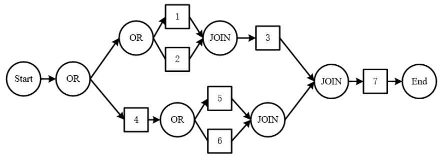
The simulation model is established by Tecnomatix Plant Simulation 11 TR3, it consists of eight workstations. Each workstation contains one multifunctional machine with equal capacity and has equal probability to be visited. The inter-arrival time follows exponential distribution with a mean of 0.4562 to achieve an average machine utilization of 90% at a scenario without disturbance. Though shop workloads fluctuate over time, a steady state is ensured on a long run suggested by [28], [29]. The due date of product is generated by adding an allowance to the arriving time. Around 30% of tardy percentage at immediate release with randomly routing decision rule is achieved as a baseline benchmark, and pretests shows the due date allowance follows uniform distribution U [30], [60]. Table 1 presents the overall features of this model.

The remaining assumptions are as follows:

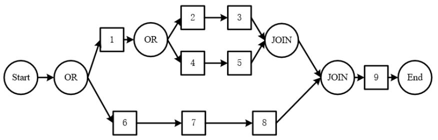
- The raw materials required for any job are always available.
- Set-up time and transition time between machines are included within processing time.
- Preemption is not allowed.
- Each job can be processed at one machine at a time, and each machine can perform at most one operation at a time.
- Product is permitted to be delivered ahead of its due date.
- Processing time of assembly operation is ignorable compared with manufacturing operation.
- The production environment considered in this problem contains different level of disturbances, including machine unavailability, uncertain rework and rush order.



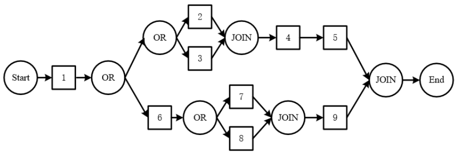
(a) Process Network Type I



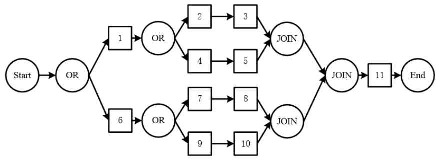
(b) Process Network Type II



(c) Process Network Type III



(d) Process Network Type IV



(e) Process Network Type V

FIGURE 6. Process plan networks in simulation model.

TABLE 2. Experimental factors and levels.

Factors	Levels
Release method	IMM BIL SLAR PR-I* PRSA-I* PR-II* PRSA-II*
Workload level*	5,6,7,8,9,10 (time units)
Routing decision rule	RS *SP STPT *SW SMW
Disturbance level	I, II, III, IV

B. EXPERIMENTAL DESIGN & PERFORMANCE MEASURES

Table 2 presents all controlled release methods and routing decision rules used in this research. Immediate release (IMM) is used as a baseline to evaluate the effectiveness of controlled release, as it will not restrict the release of new coming jobs. An important issue discussed in section II is whether routing decisions should be made by DPP or NLPP approach. IMM, BIL and SLAR can make both DPP or NLPP decisions. Instead, Periodic release methods (PR and PRSA) take the corrected aggregate approach as the workload measure, the workloads have to contribute to the specific workstation. Thereof, periodic release methods make only NLPP decisions. Periodic release methods involve two parameters, which are release period and workload level. Release period is set to 4 time-units as [21], and six workload levels are used from 5 stepwise up to 10 time-units. These workload levels are used to find the critical value of WIP, i.e. WIP level in which the overall best performance indicators can be achieved. Since workload level is only associated with

TABLE 3. **Levels of disturbances.**

Sources	Level I	Level II	Level III	Level IV
Machine unavailability	0%	2%	4%	6%
Ratio of rush order	0%	2%	4%	6%
Ratio of rework	0%	2%	4%	6%

TABLE 4. **Summary of system performance measures.**

Objectives	Name	Brief description
Lead time-based	Product Lead Time (PLT)	completion time of a product minus its arriving time
	Shop Floor Throughput Time (SFTT)	completion time of the part minus the its release time
	Assembly Delay (AD)	The mean of the product's completion time minus each parts' completion time
Due date-based	Product Tardiness (PT)	The conditional lateness, i.e. max (0, C-D), product completion time minus its due date
	Percentage of Tardy Products (PTP)	The percentage of products that are completed after its due date

periodic release methods, it is marked with asterisk (∗) behind. Similarly, not all routing decision rules can adopt NLPP approach, routing decision rules that can only be used in DPP are marked with an asterisk (∗) before.

Apart from the DFAJSC methods, experiments factors in our research also involve in the disturbance levels. according to the production environment constructed by [18], we design four-level disturbance as Table 3, and each contains three sources of disturbance, which are rush order, rework and machine unavailability.

The factor machine unavailability provides the probability that the selected machine is unable to process the operation of a job, it also represents the percentage of simulation time when machine is unavailable due to staff absence, machine breakdowns or missing raw material. When selected machine becomes unavailable, unfinished job has to wait for its recovery.

Rush order ratio means the mean ratio that a product becomes an urgent order according to customer needs, it is set as [18], the due date allowance is reduced by 70% of its original allowance.

Rework ratio indicates that when a job finishes one operation, there is a probability that it has to return to the current queue of the workstation and waits to receive small repair. The processing time of rework job is 30% percent of its original processing time.

Excluding the pretest of inter-arrival intensity and due date setting, the full factorial experiment design of our research is as much as 80 cells, including DFAJSC methods and various production environment. Each cell is replicated for 30 times, and experiment data is collected in 10800 time-units with a warming up time of 2400 time units to ensure a steady state of the simulation model. The total number of finished jobs is around 20000 when the simulation is terminated. These parameters are set to let us get a stable result at a reasonable simulation run time.

Two types of behaviors are examined in our simulation experiments, which are lead-time-based and due-date-based objectives presented in Table 4. Lead-time based objectives are the system performance measures only concerned with job's completion, including: 1) product lead time (PLT): the mean value of manufacturing cycle from a product arrival till its completion, a main criterion to evaluate the DFAJSC methods; 2) shop floor throughput time (SFTT): the mean value of elapse time from job release till its completion, this measure also indicates the total workloads as well as the congestion level in the shop floor; 3) assembly delay (AD): the mean value of each parts waiting for the final assembly of the product, an indicator to reflect the coordination between related parts. Due-date-based objectives contains percentage of tardy products (PTP) and product tardiness (PT), which are main indicators to reflect the reliability of on time delivery of the DFAJSC methods.

V. RESULTS AND ANALYSIS

A. MAIN ANALYSIS

The main target of this main analysis is to discuss the behaviors of DFAJSC methods under different levels of disturbances. In order to give an intuitive insight into the coupling effects of each routing decision rule under controlled release methods, the horizontal axis represents disturbance level and the vertical axis is the performance indicators designed in section 4, which are PLT (product lead time), AD (assembly delay), PTP (percentage of tardy products) and PT (product tardiness): IMM for Fig.7 (a1, a2) and Fig.8(a3, a4), BIL for Fig.7(b1, b2) and Fig.8(b3, b4), SLAR for Fig.7 (c1, c2) and Fig.8(c3, c4), PR for Fig.7 (d1, d2) and Fig.8(d3, d4), PRSA for Fig.7(e1, e2) and Fig.8(e3, e4). The former three controlled release (e.g. IMM, BIL, SLAR) methods make both NLPP and DPP routing decisions, and each graph contains five curves. Random selection rule is used as the benchmark and marked with cross symbol. Processing time-based rule uses the square-symbol, dash and solid lines are used to represent SP and STPT rules respectively; workload-based rule uses the circle-symbol, dash and solid lines are used to distinguish between SW and SMW rules. The latter two controlled release methods only make NLPP routing decision. Workload level is an additional parameter for periodic release methods, critical value (i.e. best performed level) is taken to make analysis. Observation 1-3 answer our first proposed question, observation 4-5 show that IOC release has smaller deterioration in high level disturbance, observation 6-7 indicate that NLPP decision is close to DPP when combined with IOC release:

(1) In the same disturbance level, the AD indicators of all controlled release based DFAJSC methods are larger than IMM, this can be observed from the curves in Fig 7 (a2-e2). Nevertheless, the main indicators PLT of IOC release methods gets better except for PR-I. Besides, all controlled release

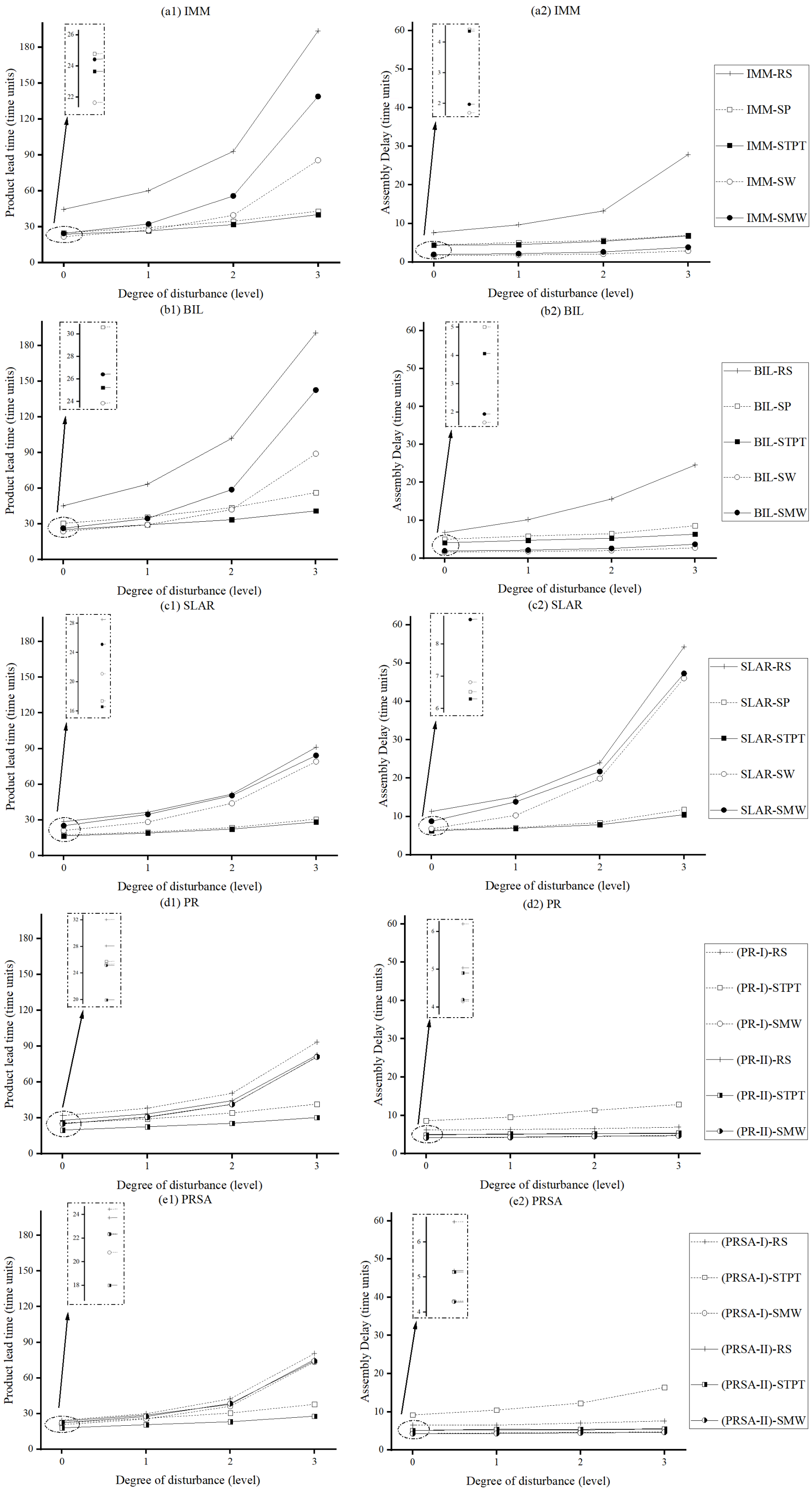


FIGURE 7. **Results of lead time-based objectives.**

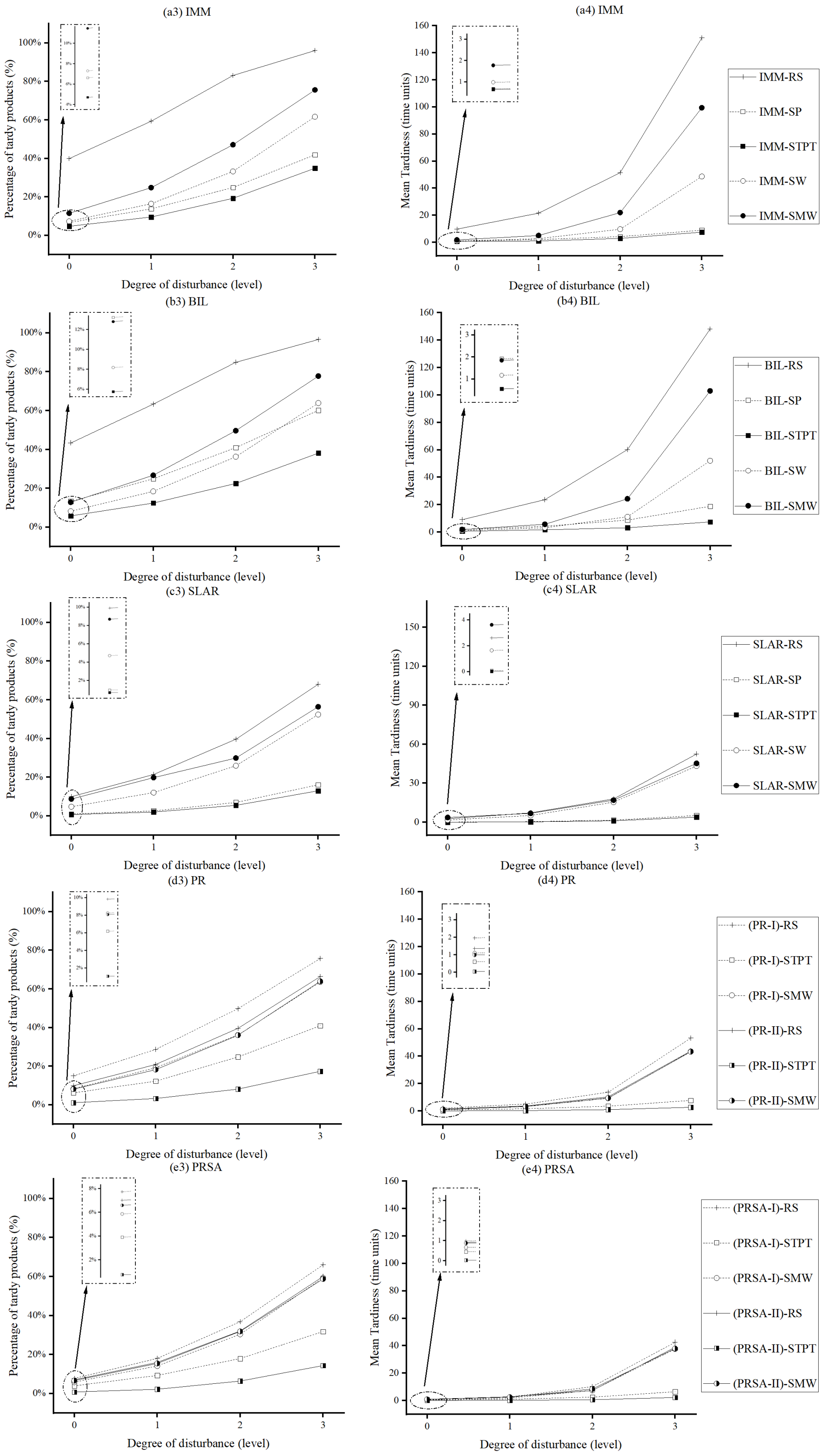


FIGURE 8. Results of due date-based objectives.

methods are advantageous over IMM at due date-based indicators (e.g. PTP, PT) apart from PR-I and BIL method, which can be observed in Fig 8. This observation suggests timely release would be restricted by controlled release methods to some extent, PR-I cannot outperform IMM as it cannot ensure the timely release of jobs. BIL performs worse than IMM due to its lack in balancing function. Improvements in delivery reliability can be obtained by controlling the WIP within a desirable level. Controlled workloads in the shop floor leads to a predictable shop flow time, which is beneficial to the coordination of related parts' progress.

(2) In the same disturbance level, SLAR method is the best performed one in main indicators (e.g. PLT, PTP and PT) among all IOC release methods, PRSA is the second best one. SLAR ensures the utilization of machines with the starvation avoidance mechanism, on the other hand, urgent continuous trigger can guarantee timely release of urgent jobs without exerting superfluous workloads fluctuation. PRSA is also an effective method, and it is much easier to implement than SLAR. SLAR demands frequent transportation as it only includes continuous release trigger, the logistic cost is bound to increase if SLAR is adopted. PRSA belongs to periodic release and can achieve similar performance measures, it would lead to a reduction in logistic cost compared with SLAR. Starvation avoidance mechanism can reduce the pool delay of those jobs rejected in periodic release for violating upper bound, this explains why PRSA has more advantages in main performance indictors than PR (see in Fig.7 c3-d3, Fig.8). As for PRSA-I and PRSA-II, the latter can always make use of process flexibility and release related jobs in time, the progress of related parts is coordinated in this way.

(3) In the same disturbance level, STPT routing decision rule has better main performance indicators than SP rule when they are integrated with the same IOC release method, the hollow square dash line (represents SP) is always larger than solid square line (represent STPT) in both Fig 7 and Fig.8. This observation indicates that global processing time information can contribute to a better performance. SW rule has a better AD indicator than any other rules, followed by SMW rule. SW rule is advantageous over SMW rule in main indicators under most circumstances, the hollow circle dash line (represents SP) is always smaller than solid circle line (represent STPT) in both Fig 7 and Fig.8. Workload is a rea-time status data, local but dynamic SW rule can select a resource with the smallest workloads.

(4) Under different disturbance levels, the deterioration of IOC release methods is smaller than IMM and time phased release, this indicates that controlling the WIP within a reasonable level is able to shield the shop floor against external disturbances. Among all IOC release methods, SLAR has the strongest resistance in PLT, PTP and PT indicators, followed by PRSA-II.

(5) Under different disturbance levels, workload-based rules have a terrific performance in low level of disturbance, SW rule is the best performed one in PLT indicators when it is incorporated with IMM in disturbance level I (see in Fig.7 -a1, Fig 8 -c3, c4). As with the increase in disturbance, the deterioration of SW rule is much larger than STPT rule, and STPT rule completely dominates SW in all indicators in disturbance level II. All processing time-based routing decision rule has a small deterioration when disturbance level increases, especially under IOC release methods.

(6) When IMM and time phased release BIL method are used, DPP routing decision is better at lead time-based indicators than NLPP routing decision. In Fig.7 b1-b2, BIL-STPT curve (NLPP) is higher in PLT indicator than BIL-SW curve (DPP) in all disturbance levels. While BIL-STPT curve is lower in due date-based indicators than BIL-SW.

(7) When IOC release methods are used, DPP routing decision is not significantly advantageous over NLPP in main indicators. SLAR-SW, SLAR-STPT and (PRSA-II)-STPT have similar performance indicators and their deteriorating trends in due date-based indicators in high level disturbance environments is also close to each other. Though SLAR-SW is slightly better at PLT indicator than (PRSA-II)-STPT, periodic release incorporated with NLPP routing decision is suggested because of its simplicity.

B. EXTENDED ANALYSIS

Previous main analysis is made by comparing the performance indicators of 30 experiments' mean value, we cannot obtain the overall performance of each experiment run. The following subsection would make extensive analysis on the stability characteristics of all controlled release methods, routing decision rule is the controlling variable and STPT rule is selected for its smaller sensitivity toward disturbance.

1) STABILITY ANALYSIS

In order to give a full description on the stability characteristics of a control release method, this subsection uses box plot to present the statistical characteristics of multiple experiments. Box plot presents the boundary value, mean value, quartile and interquartile range of a controlled release method in a disturbance level with a box symbol. The interquartile range can provide a good insight into the stability of a method. The horizontal axis of box plot is the disturbance level, and the vertical axis is a performance indicator. We aim to compare the performance stability of controlled release methods under different levels of disturbances. As presented in Fig.9, the performance stability of each method is grouped in different levels of disturbances, they are plotted with a particular texture. The stability of all indicators has different deterioration when disturbance level gets higher.

From the results of the stability for lead time-based indicators, we can draw the following conclusions: 1) though PLT indicator of BIL method is worse than IMM, BIL is much more stable at PLT than IMM as the interquartile of BIL is shorter. 2) Periodic release methods are best at stability of lead time-based indicators. 3) PRSA-II (PR-II) is better at stability of lead time-based indicators than PRSA-I (PR-I). 4) SLAR approximates the PLT indicator stability of

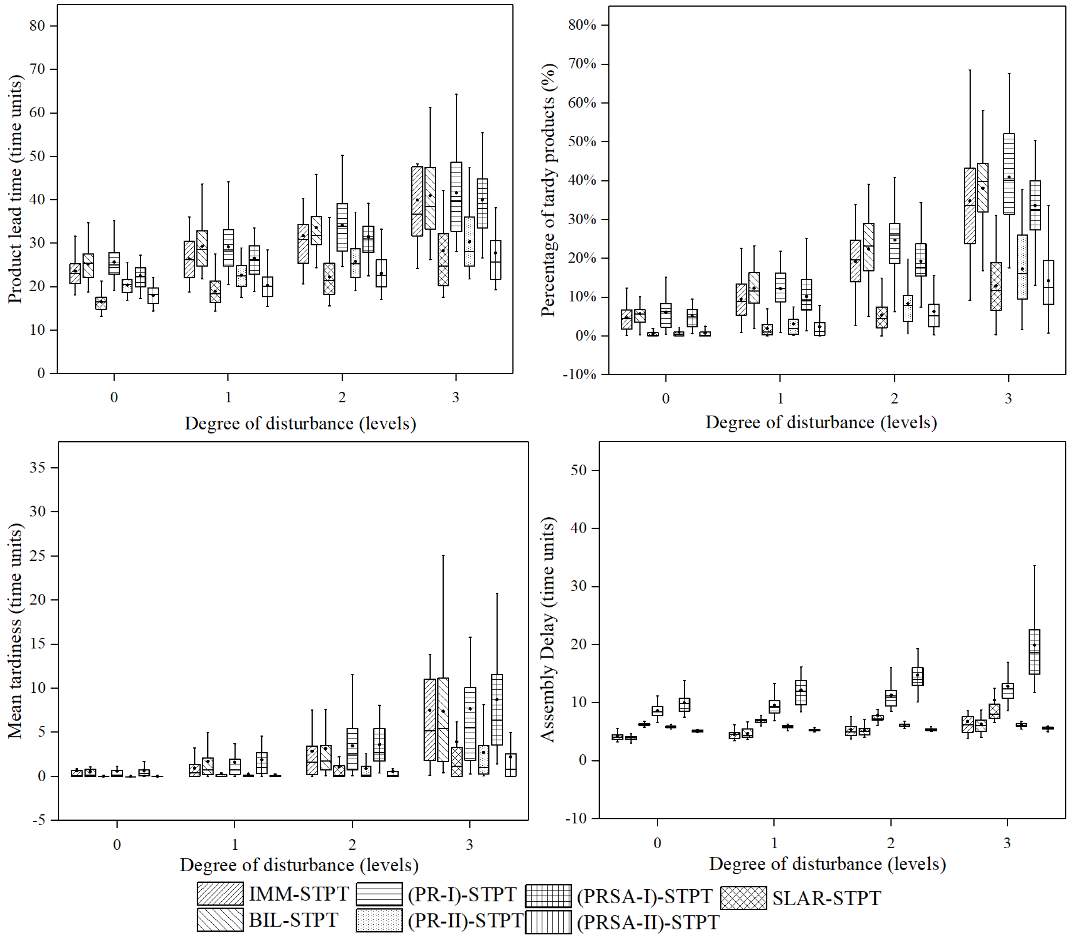


FIGURE 9. Stability comparison of controlled release methods.

TABLE 5. Workload level sensitivity for STPT-based methods.

Methods	Disturbance Level	PLT (time units)	SFTT (time units)	AD (time units)	PTP (%)	PT (time units)
(PR-I) STPT-PST	1	0.2602	2.7041	0.1807	0.5757%	0.0502
	2	0.6329	3.1524	0.4762	1.6360%	0.2462
	3	1.4199	3.6839	0.5607	1.6052%	0.8186
	4	1.9552	4.4384	1.1047	2.1641%	1.4078
(PR-II) STPT-PST	1	1.1496	2.3500	0.5834	0.1140%	0.0123
	2	1.1157	2.7300	0.5297	0.1917%	0.0361
	3	1.0880	3.2311	0.5459	0.3754%	0.0251
	4	1.0229	3.6843	0.4527	0.7081%	0.2027
(PRSA-I) STPT-PST	1	0.1948	2.2632	0.3403	0.5877%	0.1457
	2	0.2637	2.7821	0.6696	0.4269%	0.3619
	3	0.3652	3.4301	0.8985	0.5492%	0.2946
	4	0.6227	4.3498	1.4672	1.1091%	0.7675
(PRSA-II) STPT-PST	1	0.8930	1.7582	0.5452	0.0694%	0.0045
	2	0.9710	2.1872	0.5934	0.3113%	0.0331
	3	1.0821	2.5850	0.5984	0.4314%	0.0937
	4	1.2438	3.2915	0.5135	0.7135%	0.1580

PRSA-II, but its AD indicator stability falls behind periodic release methods that makes NLPP decisions.

As for the stability for due date-based indicators, three obvious observations can be made: 1) PRSA-II method is best performed at the stability of PTP and PT indicators, followed by SLAR method; 2) Periodic release methods with starvation avoidance mechanism are superior to pure periodic release methods in due date-based indicators stability. This can be attributed to the starvation avoidance mechanism, delayed released jobs are pulled into the shop by continuous trigger

TABLE 6. **Workload level sensitivity for SMW-based methods.**

Methods	Disturbance Level	PLT (time units)	SFTT (time units)	AD (time units)	PTP (%)	PT (time units)
(PR-I) STPT-PST	1	0.1346	2.7929	0.1277	0.4162%	0.0720
	2	0.4416	3.4028	0.1555	0.7985%	0.2551
	3	1.7575	4.1639	0.1897	1.9558%	1.4983
	4	8.3972	5.1020	0.3924	2.5396%	8.2117
(PR-II) STPT-PST	1	0.2357	2.6203	0.1075	0.3323%	0.0786
	2	0.3731	3.2891	0.1814	0.8778%	0.1512
	3	1.3545	4.0339	0.1700	1.1281%	1.0860
	4	4.7834	4.9588	0.2213	1.7947%	4.7435
(PRSA-I) STPT-PST	1	0.4405	2.2077	0.1033	0.2096%	0.0743
	2	0.6057	2.8049	0.1277	0.5339%	0.1860
	3	0.6354	3.7602	0.1518	0.8805%	0.4030
	4	1.2174	4.9580	0.2451	1.0208%	1.0602
(PRSA-II) STPT-PST	1	0.4099	2.2266	0.0922	0.2174%	0.0297
	2	0.4352	2.8808	0.1530	0.7623%	0.1589
	3	0.4181	3.6902	0.2028	0.9263%	0.3672
	4	1.7946	4.9003	0.1774	1.1923%	1.5237

to achieve a better coordination of related parts' progress; 3) PRSA-II (PR-II) is better at due date-based indicators stability than PRSA-II (PR-II).

We may arrive at a conclusion that IOC release methods are much more stable at main indicators than IMM and BIL methods. SLAR is the best performed IOC method, meanwhile SLAR is considered as the most difficult one to implement, its main difficulty lies in the determination of job's urgency, besides, frequent triggering of pulling jobs from the pool would increase the cost in logistics. Thus, periodic release is the overall best option for implementation in flexible assembly job shop for its simplicity and stability.

2) SENSITIVITY ANALYSIS FOR PERIODIC RELEASE

In previous section of experiment design for periodic release, different workload levels are used to find a critical value. As one of the applicable control release methods, periodic release methods can obtain best main performance in a certain level of WIP. Yet the WIP level is directly influenced by workload level for periodic release methods. Thereof, we would further analyze the workload level sensitivity of periodic release methods. We design a measure of workload level sensitivity for each indicator, and the formulation is as follows:

$$S = \sum_{n \in N} (P_n - P_{\min}) / |N| \tag{7}$$

In equation (7), P represents the performance indicators designed in section 4 (e.g. PLT, PTP, PT and AD). Sensitivity reflects the difference between each workload level's indicator and its critical value for one specific method, we intend to measure the sensitivity of each indicator in different disturbance levels. Results of STPT-based and SMW-based methods' workload level sensitivity are given in Table 5 and Table 6 respectively.

From the results of workload level sensitivity for STPT-based DFAJSC methods given in Table 5, the most obvious conclusion is that each DFAJSC method gets more sensitive to the workload level as with the increase of disturbances.

Two observations can be made from the results: 1) The due date-based indicators of PRSA-I (PR-I) are more sensitive to the change of workload level in all levels of disturbances than PRSA-II (PR-II); 2) As for the lead time-based indicators, PR-II is less sensible to workload level in environments with low level of disturbances, but PR-II's workload level sensitivity is larger than PR-I's in environments with high level of disturbance. The PRSA-II is less sensible than PRSA-I in all levels of disturbance, but their difference gets smaller as with the increase of disturbance.

Another conclusion we can draw is that starvation avoidance mechanism can reduce the workload sensitivity, as the indicators of PRSA method are less sensible than those of PR method. Starvation avoidance can pull a job directly from the pool to a starving workstation regardless of the workload level, it can contribute to the reduction in workload level sensitivity.

By comparing Table 5 and Table 6, we can draw a conclusion that all periodic release methods are less sensible to the workload level when they are integrated with STPT rules. Similar observations can be obtained for SMW based methods: 1) PRSA-II (PR-II) is less sensible to the workload level than PRSA-I (PR-I) in all degrees of disturbance; 2) periodic release methods with starvation avoidance are less sensible to workload level than original versions.

VI. CONCLUSION

Considering the complexity of scheduling in FAJS, prior studies focus on proposing new search-based algorithm to find a feasible schedule with acceptable time consumption, whereas this approach has been theoretically testified in small and medium sized instance. The main contribution of this paper is that we establish a hierarchical control framework for dynamic flexible assembly job shop characterized by large-scale instance and disturbances, our study started from improving existing controlled release methods to make them adjustable for FAJS. Based on the improved controlled release methods, we investigate two alternative approaches (DPP and NLPP) for integrating routing decision with release decision. By discrete event simulation, we evaluate all DFAJSC methods in different levels of disturbances.

From the simulation results, we may arrive at three conclusions corresponding to our three questions: 1) delivery reliability cannot be improved simply by postponing the release of new arriving jobs. Controlling release workloads within a desirable level leads to predictable shop flow time, product lead time and tardy percentage is in turn reduced, this explain IOC release dominates BIL and IMM; 2) Performances of IOC release methods fall down slower than time phased release when disturbance level goes up. SLAR is the best performed one at disturbance resistance, but PRSA is advocated due to its similar performance and simplicity; 3) DPP approach does not have significant advantages over NLPP when integrated with IOC release, and STPT rule is the best performed routing decision rules in most scenarios. In view of this, (PRSA-II)-STPT is the overall most suitable DFAJSC methods in practice.

This paper uses priority rules to determine the release priority simply to improve computing efficiency, future works could apply meta-heuristics and even exact algorithms to improve optimality of release decision. Besides, this paper only uses manual designed rules to investigate the behaviors of job and shop features on different scheduling criteria, evolutionary algorithm could be adopted in future works based on the conclusions of this paper.

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