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Robotic material handler scheduling in flexible manufacturing systems for mass customization

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ABSTRACT

The scheduling problem of robotic material handlers in flexible manufacturing systems (FMSs) is NP-hard. This paper proposes a state-dependent algorithm for the FMS robot scheduling problem in make-to-order (MTO) environments for mass customization (MC). A mathematical model of the problem is formulated. A computational study of the proposed algorithm is performed. The algorithm is compared to an effective FMS robot scheduling rule, the shortest remaining processing time first (SRPF) rule. The results reveal the effectiveness of the algorithm in increasing the productivity-based measures of the FMS. Practical application insights are discussed. Further research is also provided.

1. Introduction

Enterprises place more efforts on customer requests to obtain competitive advantage in global competition. Mass customization (MC) is aimed to give customers exactly what they want with low-cost, high-quality in ever changing environments [1]. Customer co-design and customer specified manufacturing are often performed in MC systems and make-to-order (MTO) or build-to-order (BTO) processes are often utilized [2–4].

A flexible manufacturing system (FMS) is an integrated, computer-controlled complex of automated material handling devices and numerically controlled machine tools that can simultaneously process medium-sized volumes of a variety of part types [5]. FMSs can produce product components within its wide envelope of variety and can be used to automate MC [1]. The design and operation of FMSs involve the problems that can be formulated as quantitative problems and approached through operations research methods. The problems are categorized as design, planning, scheduling, and control problems [6].

Workload balancing is recognized to eliminate bottlenecks and to increase the production for the FMS planning and scheduling problems. Stecke [5] defined five production planning problems for FMSs and addressed specifically the FMS grouping and loading problems with workload balancing as an objective for FMS loading. Other examples of the application of workload balancing to FMS planning and scheduling are described in [7–9].

Most of the scheduling problems in FMSs can be classified as part input sequencing, machine scheduling, and scheduling of material handlers (such as robots, AGVs, RGVs, etc). There can be several machines requesting services of material handling equipment simultaneously and there will be conflicts in which a machine will have to wait while another is served in a flexible manufacturing cell (FMC), i.e., a small FMS [10,11]. The scheduling problem of robotic material handlers in FMCs is NP-hard [10,11]. It is even harder in MTO environments because customer orders arrive dynamically in the environments. We propose a heuristic-based algorithm for the FMS robot scheduling problem in MTO environments for MC. The FMS is characterized with multiple machines, multiple part types, non-unidirectional flow, and dynamic arrival of parts. The proposed algorithm applies dynamic workload balancing and adopts the shortest remaining processing time first (SRPF) rule.

The remainder of the paper is as follows: Section 2 provides a brief review of relevant literature in robot scheduling; Section 3 describes a mathematical model of the problem; a state-dependent algorithm is proposed in Section 4; Section 5 provides a computational study; conclusions, managerial implications, and further research are provided in Section 6.

2. Relevant literature in robot scheduling

A robotic flowshop possesses one or more robots moving parts among machines and input/output stations and all parts are

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sequentially processed [12]. The scheduling problem in robotic flowshops is investigated. Studies include the work by Sethi et al., Crama and Van De Klundert, Crama et al., Kumar et al., and Che and Chu [12–16].

Researchers considered the formulation of the scheduling problem in robotic cells as the parametric critical path (PCP) problem such as Kats et al. [17]. Researchers also considered the problem as the extension of the traveling salesman problem (TSP) with examples [18,19]. Investigators studied the robot scheduling problem with different situations including parallel machines [20] and multiple robots [16]. Different types of robots were also included such as mobile robots [21] and double-gripper gantry robots [22].

Investigation on robot scheduling in FMSs includes those [10,11,18,23,24]. Particularly, King et al. [11] developed a branch and bound approach to optimize robot moves in an FMC of two machines and found that the approach is not very effective for large problems. Park [10] performed a simulation study of robot movement decision rules in an FMC and identified the SRPF rule as the best robot scheduling rule for both mean flowtime and makespan among six rules examined.

Numerous researchers have investigated the scheduling problem in robotic cells. Related research papers are many. The above only describes briefly the typical studies in the literature. In summary, various situations are considered such as identical part type and multiple part types; single robot and multiple robots; parallel machines and non-parallel machines; robotic flowshops and FMSs. Various forms of the problem are considered such as the formulation of the problem as the cyclic scheduling problem, as the PCP problem, and as TSP. A variety of approaches are applied to the problem such as the dispatching rule, heuristic, branch and bound, dynamic programming, knowledge-based, neural network, polynomial algorithm, and genetic algorithm approach.

3. Mathematical model

A mathematical model is formulated for the FMS robot scheduling problem. The FMS possesses M non-identical machines. A robot is utilized to transport parts. The FMS manufactures parts of N types and part routings are non-unidirectional. Parts arrive at the FMS dynamically. FMS studies in dynamic environments can be found [25–27].

The objective of the problem is to maximize production, that is, total parts produced in a time duration specified. For robot scheduling, operation processing on machines is not considered. The subscripts, parameters, and variables in the mathematical model are listed in Table 1. r_i represents part r of type i. The problem is stated as follows:

$$\text{Maximize } \psi \quad (1)$$

subject to

$$c_{r,i} = \sum_{j=1}^{M} s_{r,i,j} n_{j,K_i} + p_{i,K_i}, \quad \forall r \geq 1, \quad 1 \leq i \leq N, \quad (2)$$

$$f_{r,i} = c_{r,i} - r_{r,i,1}, \quad \forall r \geq 1, \quad 1 \leq i \leq N, \quad (3)$$

$$c_{r,i} - a_{r,i} \geq f_{r,i}, \quad \forall r \geq 1, \quad 1 \leq i \leq N, \quad (4)$$

$$\sum_{k=1}^{K_i} (p_{i,k} + m_{r,i,k}) \leq f_{r,i}, \quad \forall r \geq 1, \quad 1 \leq i \leq N, \quad (5)$$

$$\sum_{k=1}^{K_i} r_{r,i,k} n_{j,k} + \sum_{k=1}^{K_i} m_{r,i,k} n_{j,k} \leq s_{r,i,j}, \quad \forall r \geq 1, \quad 1 \leq i \leq N, \quad 1 \leq j \leq M, \quad (6)$$

Table 1
Subscripts, parameters, and decision variables in mathematical model.

Symbol	Definition
Indices	
i	Part type, $i=1,2,\ldots,N$
j	Machine, $j=1,2,\ldots,M$
k	Operation, $k=1,2,\ldots,K_i$
r	Part of a type, $r=1,2,\ldots$
Parameters	
$a_{r,i}$	Arriving time of r_i
$p_{i,k}$	Processing time of operation k of type i
$m_{r,i,k}$	Time of robot move for operation k of r_i
$n_{j,k}$	$n_{j,k} = \begin{cases} 1, & \text{operation } k \text{ is processed at machine } j; \\ 0, & \text{otherwise.} \end{cases}$
Variables	
ψ	Total parts produced
$s_{r,i,j}$	Starting time at machine j of r_i
$c_{r,i}$	Completion time of r_i
$f_{r,i}$	Flowtime of r_i
Decision variables	
$r_{r,i,k}$	Starting time of robot move for operation k of r_i

$$s_{r,i,j} + \sum_{k=1}^{K_i} p_{i,k} n_{j,k} \leq \sum_{k=1}^{K_i} r_{r,i,k+1} n_{j,k}, \quad \forall r \geq 1, \quad 1 \leq i \leq N, \quad 1 \leq j \leq M, \quad (7)$$

$$r_{r,i,k} \geq 0, \quad \forall r \geq 1, \quad 1 \leq i \leq N, \quad 1 \leq k \leq K_i. \quad (8)$$

Constraint (2) describes that the completion time of a part is equal to the starting time of the last operation of the part plus its processing time of the last operation. Constraint (3) measures the flowtime of a part, which is a time interval between starting and completing of the part. Constraint (4) reflects a lapse between the arrival of a part and the starting of processing of the part. Constraint (5) indicates that there is waiting in part processing and robot service. Constraint (6) describes that part processing may not start immediately. Constraint (7) indicates that a robot move may not start immediately. Constraint (8) ensures a positive starting time of a robot move.

4. Proposed robot scheduling algorithm

As the mathematical model in the previous section indicated, the problem studied here is NP-hard. Generally speaking, the optimization approach is inefficient or even impossible for an NP-hard problem. Because heuristics can be used to provide good and quick solutions, we propose a heuristic-based algorithm for the problem. We call it the state-dependent robot scheduling algorithm (SDRSA).

Workload balancing is recognized to be able to eliminate bottlenecks, and to increase production in FMSs. Stecke and Morin [7] illustrated that workload balancing maximizes expected production in certain types of FMSs. In addition, the SRPF rule can minimize both mean flowtime and makespan for robot scheduling in an FMC [10]. Production can be increased if mean flowtime is reduced in a given production duration. Therefore, the strategy of dynamic workload balancing and the SRPF rule are applied in the algorithm. Also, the first in first out (FIFO) rule is applied when many parts have the same priority as the result of dynamic workload balancing and SRPF. The dynamic workload of a machine is defined as the total time of remaining operations of parts inputted into the FMS but not finished on the corresponding machine. Dynamic workload is dependent on the current status of an operating FMS and can be obtained