Scheduling with Tool Switching in Flexible Manufacturing Systems

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Abstract: In our problem, there are a number of jobs to be processed on parallel computer numerically controlled machines. Each job requires a set of tools and the required tools must be loaded to process the jobs. The machines have limited tool magazine capacities and the number of tools available in the system is limited due to economic restrictions, which leads to the need for switching tools. We assume that the tool switching time constitutes a significant portion of total processing time and does not depend on the number or type of tools changed. The problem is to assign the jobs and the required tools to machines and determine the schedule so that the makespan is minimized. A mathematical model and a heuristic approach based on the decomposition of the problem are developed.

1 INTRODUCTION

Flexible Manufacturing Systems (FMSs) are integrated systems of computer numerically controlled (CNC) machines and automated material handling devices. In an FMS, machines are capable of processing different types of operations as long as the required tools are loaded. Tool management is a vital issue in FMS management due to complexities brought by the limitations. The number of tools available in the system is limited because of economic restrictions. The number of copies of each tool may be smaller than the number of machines. Also the number of tool slots in the tool magazines of the machines is limited. These restrictions lead to the requirement of tool switches.

There are several problems that may occur in a flexible manufacturing environment. (Crama, 1997) and (Blazewicz and Finke, 1994) provide review of problems that arise in flexible manufacturing systems. This paper considers tool loading, operation scheduling and tool switching problems at the same time.

There are a number of studies that consider the job sequencing and tool switching problem on a single machine. Some examples are due to (Crama et al., 1994), (Laporte et al., 2004), (Ecker and Gupta, 2005) and (Karakayalı and Azizoğlu, 2006). Another group of studies in the literature approach the problems in a sequential way including (Agnetis et al., 1997), (Kellerer and Strusevich, 2004) and (Avci and Akturk, 1996).

2 PROBLEM DEFINITION

Consider n jobs to be processed on m parallel CNC machines. There is no precedence relation between the jobs that is defined in advance. A job can be assigned to exactly one machine and pre-emption is not allowed. Every machine can process every job; however the processing time of a job on different machines may vary. We assume that tool switching requires a significant amount of time and should be considered when determining the schedule. Also tool switching time is assumed to be independent from number and type of the tools changed.

The problem is to schedule the jobs on parallel machines with their required tools so as to minimize makespan.

3 MATHEMATICAL MODEL

In this section, we present the mathematical programming model of the problem defined above. First, we define the decision variables and parameters used in the model. A group is a set of jobs that are processed between two consecutive tool switches.

Parameters:

$l(i)$: the set of tools required by job i

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p_{ij}: processing time of job i on machine j
ts: tool switching time
c: tool magazine capacity
Decision variables:
$Cmax$: makespan
X_{ig}: 1, if job i is assigned to group g; 0, otherwise
$W_{h_k g}$: 1, if copy h of tool k is assigned to group g; 0, otherwise
Y_{gbj}: 1, if group g is processed before group b on machine j; 0, otherwise
Z_{gj}: 1, if group g is processed on machine j; 0, otherwise
V_{gb}: 1, if groups g and b use the same tool and group g is processed before group b; 0, otherwise
C_g : completion time of group g $(C_g \geq 0)$
S_{gj} : starting time of group g on machine j $(S_{gj} \geq 0)$
pt_{gj}: total processing time of group g on machine j $(pt_{gj} \geq 0)$

The mathematical model is given below:

$$\text{Min } Cmax \tag{1}$$

subject to

$$\sum_{g \in G} X_{ig} = 1 \quad \forall i \tag{2}$$

$$\sum_{h_k} \sum_{k \in K} W_{h_k g} \leq c \quad \forall g \tag{3}$$

$$X_{ig} \leq \sum_{h_k} W_{h_k g} \quad \forall i, g, k \in l(i) \tag{4}$$

$$\text{Cmax} \geq C_g \quad \forall g \tag{5}$$

$$pt_{gj} \geq \sum_i p_{ij} \left(X_{ig} + Z_{gj} - 1 \right) \quad \forall g, j \tag{6}$$

$$C_g = ts + \sum_j \left(S_{gj} + pt_{gj} \right) \quad \forall g \tag{7}$$

$$S_{gj} \geq S_{bj} + pt_{bj} + ts - M\left(Y_{gbj}\right) - M\left(1 - Z_{bj}\right) - M\left(1 - Z_{gj}\right) \quad \forall g \neq b, j \tag{8}$$

$$Z_{bj} + Z_{gj} \geq 2\left(Y_{bgj} + Y_{gbj}\right) \quad \forall g \neq b, j \tag{9}$$

$$Z_{bj} + Z_{gj} \leq Y_{bgj} + Y_{gbj} + 1 \quad \forall g \neq b, j \tag{10}$$

$$S_{gj} \leq M\left(Z_{gj}\right) \quad \forall g, j \tag{11}$$

$$\sum_j Z_{gj} \leq 1 \quad \forall g \tag{12}$$

$$\sum_j Z_{gj} \geq X_{ig} \quad \forall i, g \tag{13}$$

$$Z_{gj} \leq \sum_i X_{ig} \quad \forall g, j \tag{14}$$

$$\sum_j S_{bj} \geq \sum_j \left(S_{gj} + ts + pt_{gj} \right) - M\left(2 - \left(W_{h_k g} + W_{h_k b}\right)\right) - M\left(1 - V_{gb}\right) \quad \forall g, b \tag{15}$$

$$V_{gb} + V_{bg} \leq 1 \quad \forall g, b \tag{16}$$

$$W_{h_k g} + W_{h_k b} \leq 2\left(V_{bg} + V_{gb}\right) \quad \forall g, b \tag{17}$$

Objective (1) is to minimize makespan. Each job is assigned to one group (2). The tool magazine capacities of the machines are not exceeded (3). Required tools of the jobs in a group are loaded on the machine (4). Makespan is the largest completion time among all groups (5). The processing time of a group on a machine is the summation of processing times of the jobs in that group on that machine (6). The completion time of a group is the summation of tool switching time, starting time and processing time of the jobs (7). Starting times of any two groups cannot coincide if they are processed on the same machine (8-10). Starting time of a group on a machine can be positive only if the group is assigned to the machine (11). Each group can be assigned to at most one machine (12). If a job is assigned to a group, then that group must be assigned to a machine (13). If no job is assigned to a group, then that should not be assigned to any machine (14). The processing times of two groups using the same tool copy cannot coincide (15-17).

4 HEURISTIC APPROACH

In this section, a heuristic method, based on the decomposition of the problem into two subproblems, is presented. The first subproblem only considers assigning jobs to groups while minimizing the number of groups, which is called job grouping problem. While minimizing the number of groups, the aim is to minimize the time required for tool switches. The second subproblem schedules groups and tools using the assignment of the first subproblem and considering the tool switching time with the aim of minimizing makespan. Each of the two subproblems is proved to be NP-Hard. Therefore a heuristic approach is used to obtain solution to the first subproblem, whereas for the second subproblem constraint programming and tabu search methods are suggested.

4.1 Subproblem 1: Job Grouping

Stepwise procedure of the heuristic developed for the first subproblem is given below.

U_{ij}: total number of common tools between jobs i and j
$l(i)$: set of tools required to process job i
c: tool magazine capacity of machines
w_g: set of tools required by the jobs in group g
A_g: set of jobs assigned to a group g
D: set of jobs not assigned to any group

0. Find U_{ij} for all i and j. Set g=1, A_g=∅ for all g, D={1, 2, ..., n} and w_g=∅ for all g.
1. Let max $\{U_{ij}\}$= $U_{i'j'}$.
  1.1. If $(\left|l(i')\cup l(i')\right| \le c$, then assign jobs i' and j' to group g.
  1.2. Remove jobs i' and j' from set D, and add to set A_g.
  1.3. Set $w_g = l(i')\cup l(i')$.
  1.4. If $|w_g|<c$, go to Step 2. If $|w_g|=c$, go to Step 3.
2. Find unassigned job k that has the maximum number of common tools with the jobs in set A_g.
  2.1. If $|w_g \cup l(k)| \le c$, assign job k to group g. Remove job k from set D and add to set A_g. Set $w_g = w_g \cup l(k)$.
  2.2. If $|w_g|<c$, repeat Step 2. If $|w_g|=c$, go to Step 3.
3. Find a job h such that $l(h) \subseteq w_g$. Assign job h to group g. Remove job h from set D and add to set A_g. Repeat until no more jobs can be added to group g.
4. Update U_{ij}, set g=g+1 and go to Step 1.

4.2 Subproblem 2: Scheduling

(Özpeynirci and Gökgür, 2011) and (Gökgür *et al.,* 2012) work on the problem of scheduling jobs on parallel CNC machines with tool assignment. They develop a tabu search algorithm and a constraint programming model, respectively, for the solution of the problem. Our scheduling subproblem is similar to their problem if we consider groups as jobs and add the tool switching times. Hence, for the solution of the second subproblem, we can benefit from their solution methods with slight modifications.

4.2.1 Constraint Programming Approach

A group can be viewed as an activity which contains its starting, duration and ending time. Each group requires one copy of required tools and is assigned to one machine. Tool-copy pairs and machines can be seen unary resource with "*noOverlap*" constraint and cumulative with "*pulse*" constraint resource, respectively. There is also *Alternative* global constraint that provides the assignment of an activity to one of the resources in the list.

We use the same modelling language used by (Gökgür *et al.,* 2012) for the constraint programming model with some modifications that is also suitable for (IBM ILOG CP Optimizer 2.3). The constraint programming model is shown below.

Parameters:
$l(g)$: the set of tools required by group g
p_{gj}: processing time of group g on machine j

Decision Variables:

$Activity\ J_g, \forall g \in 1,\ldots,G$

$Resource\ M_j, \forall j \in 1,\ldots,m$

$Resource\ T_{kc}, \forall k \in 1,\ldots,t, \forall c \in \{1,\ldots,r_k\}$

$Minimize \max\{\text{endOf}(J_1),\ldots,\text{endOf}(J_G)\}$

Subject to

$noOverlap(M_j), \forall j$

$noOverlap(T_{kc}), \forall k, c$

$Alternative(J_g, [M_1,\ldots,M_m], [p_{g1},\ldots,p_{gm}]), \forall g \in \{1,\ldots,G\}$

$Alternative(J_g, [T_{k1},\ldots,T_{kr_k}]), \forall g \in \{1,\ldots,G\}, \forall k \in l(g)$

4.2.2 Tabu Search Approach

Based on (output of first sub-problem), tabu search finds schedule of groups and tools on parallel machines.

Solution representation is the sequence of groups that will be processed on each machine. To obtain initial solution, a greedy heuristic is developed that selects groups according to a priority rule and assigns to the first available machine with required tools. Procedure of the greedy heuristic is given below.

0. Let S_0 be the set of groups that are not assigned to a machine yet, and S_1 be the set of groups that are assigned to a machine.
  List the groups in non-decreasing order of total processing times of jobs included in the group. Select the first m groups from the list and assign each one to one machine. Update S_0 and S_1.
1. Find the machine that becomes idle first. Let the machine be j.
  Calculate the priority values for all groups on machine j using the following equation:

$$\pi_{gj} = p_{gj} \times a_{gj} \times b_{gj}^2$$

  where π_{gj} is the priority value of group g on

machine j, p_{gj} is the total processing times of jobs on machine j included in group g, a_{gj} is the number of tools needed additionally to assign group g to machine j that we have available copy and b_{gj} is the number of tools needed additionally to assign group g to machine j that we do not have available copy.
Select the job with minimum priority value. Let the group be g'.

2. Remove the tools from machine j that are not elements of $w_{g'}$.
3. Load the tools that are elements of $w_{g'}$ to machine j and that are not already loaded on machine j.
If a required tool is not free, then delay the starting time of group g' on machine j until the tool is free.
Go to Step 1.

There are two neighbourhood structures that generate a solution. The first neighbourhood structure is to swap two groups without considering whether they are assigned to different machines or not. The second structure is to remove a group from its position and insert to another place on the same or different machine. Infeasible solutions are not considered due to complex structure of tooling.

Tabu attributes for this problem is the following; when a group is assigned to a position on a machine, removing that group from its place is called tabu for a specified number of iterations. Tabu tenure is set to $\sqrt{\frac{n}{c/\bar{l}}}$, where $\bar{l}$ is the average number of tools required by jobs.

5 CONCLUSIONS

In this study, we consider the scheduling of jobs on a group of parallel CNC machines together with their required tools in a flexible manufacturing system. We also consider the tool switches between the jobs. Our objective is to minimize the makespan. We provide the mathematical model of the problem and propose a heuristic approach based on decomposing the problem into two subproblems: forming the job groups and scheduling the groups on the machines.

In the future, we are planning to design computational experiments and evaluate the performance of our heuristic approach. Next, we will work on efficient exact solution approaches such as constraint programming.

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