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Machine Load Balancing Based on Maximizing the Throughput in a Flexible Manufacturing Environment

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Abstract

Operational effectiveness of flexible manufacturing systems largely depends on a good quality solution to the machine loading problem (MLP). Thus, this problem is considered as a vital pre-release decision making problem in manufacturing environment. Despite the researches which addressed this issue mainly to obtain a near optimal solution, this paper formulates machine loading problem as a linear mathematical programming model to determine an exact solution for it. The objective function of the proposed model is to maximize the profitability of the system based on maximizing the throughput. The proposed model has been coded in Lingo 8 Software environment. Some benchmark problems are solved through the proposed model with Lingo Software and results are compared with those available in the literature. The solution of the proposed model obtains in an acceptable time and it can result in a significant cost-effectiveness in a mass production environment.

Keywords: *Linear mathematically programming; Lingo coding; Machine allocating; Machine load balancing*

1. Introduction

Throughput effective production has become a key issue in manufacturing environments for striving in the hard global competitive markets. Loading decisions play an important role in throughput effective production by processing the job in a feasible sequencing schedule with the proper utilization of resources. Effective loading decisions are particularly important in the large, complex manufacturing systems encountered in high technology industries dealing with processing of customized products and many others, where, simple manual techniques are unlikely to yield good results [1].

According to Stecke [2], machine loading problem is one of six post-release decisions of a flexible manufacturing system that is known for its computational complexity and high variability. Due to inherent generality of FMS, it becomes necessary to define the configuration of an FMS. A typical FMS unit includes 5–25 Numerical Control (NC) machines, a central storage system and an automated material handling system. A computer system is used to control the above components of FMS.

In general, two types of operational decisions (pre-release decision and post-release decision) are associated with operations of FMS. Pre-arrangement of jobs and tools comes under the category of pre-release decision of FMS whereas routing and sequencing of jobs comes under post-release decision of FMS. Various post-release decisions of FMS include: Job selection, Machine grouping, Determination of production ratio, Batching of the jobs, Allocation of pallets and fixtures and Allocation of operations and tools among machines (loading problem).

Hwang et al. [3] investigated the production planning problem and found that two sub-problems namely job selection and machine loading are critically important. Decisions pertaining to loading problem receive their inputs from the preceding decision levels (such as grouping of resources, selection of part-mix, and aggregate planning). These strategic antecedents generate inputs to the succeeding decisions related to scheduling resources, and dynamic operations planning and control. Hence, it is clear that loading decision acts as important link between strategic and operational level decisions in the manufacturing environment [4]. This paper aims to solve the well known FMS machine loading problem, by maximizing throughput (equivalent to the sum of the batch size of the selected jobs) and thereby, maximizes the profitability of the production system. The model presented in this paper permits machines to be over loaded and under loaded such as a real production environment. This objective is the measurement that commonly adopted to reflect the system efficiency.

Machine loading problem is mainly concerned with

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assignment of jobs and tools on machines. This entitles operation of selected jobs from a given set of jobs along with required tool slots while satisfying the technological constraints namely available machining time and tool slots. The combination of job sequencing and operation allocation on machine makes the machine loading problem a NP-hard problem [5]. The complexity of the Machine loading problem is so immense that even for 8–10 jobs there can be a huge possible operation-machine allocation combinations. The huge solution space slows the search convergence, and undermines the possibility to get close to the optimal solution.

Stecke [2] formulated the loading problem in a flexible manufacturing system as a non-linear mixed integer program with the objective of balancing the workloads. Kusiak [6], Stecke and Morian [7], Singhal et al. [8] and van Looveren et al. [9] have addressed interrelationship of various decisions and their hierarchies in FMS. Kim and yano [10] also presented a number of heuristic approaches for loading problems in flexible manufacturing systems; Kim and Yano [11] also presented a model of the loading problem in FMS with unequal workload targets across machine groups, and demonstrated how an existing branch-and-bound algorithm for the workload balancing objective may be used to solve the model. Stecke and Raman [12] presented a queuing network production planning model to determine the optimal machine work load assignments in an FMS. Liang [13] proposed a two stage approach to the joint problem of part selection, machine loading and machine speed selection problem in FMS. In the first stage, the mathematical model solves the part selection and machine loading problem, whereas in the second stage, it determines the optimal cutting speed for all job-tool-machine combinations.

Ammons et al. [14] resolved the loading problem considering a bi-criteria objective of balancing workload and minimizing work stations visits whereas Shankar and Tzen [15] consider balancing workload and meeting due-date of part types. Tiwari et al. [16] and Mukhopadhyay et al. [17] tackle machine loading problem using heuristic approaches with an objective of minimizing system unbalance and maximizing throughput. Prakash et al. [18] used a modified immune algorithm for machine loading problem with considering minimization of system unbalance and maximization of throughput as their objective function by taking into account the technological constraints such as available machining time and tool slots on machines and considered both under-utilized and over-utilized times on machines for calculating system unbalance.

In recent years success has been achieved by nature inspired intelligent random search techniques to tackle the complex combinatorial problems (e.g., example, Genetic Algorithms (GAs), Ant Colony Optimization (ACO) and Immune Algorithms (IAs)).

In article presented by Prakash et al. [18] encouraged by the applications of a novel evolutionary technique, i.e. Artificial Immune System (AIS) have been considered in that article. Due to AIS self organizing and learning capability, this technique has been widely used in real world applications such as data manipulation, pattern recognition, machine learning, evolutionary computation, etc. [19]. Castro and Zuben [19] also found that the existing immune algorithms are not very interactive and need much more computational time to reach the optimal solution. In response to their claims, a modified version of Immune Algorithm entitled as ‘Modified immune algorithm (MIA)’ is proposed by Prakash et al. [18] that results in better computing results with reduced computational cost. The modifications performed in the proposed algorithm are basically dealing with the existing drawbacks related to the basic driving forces of the immune algorithms.

In summary, the machine loading problems pertaining to automated manufacturing systems belong to the category of NP-hard problems. To illustrate the complexity associated with machine loading problems, assume the data shown in Table 1.

Table 1. Description of problem no.10 (adopted from Mukhopadhayay et al.[17]).

Job	Batch size	Operation number	Unit processing time	Tool slot needed	Machine number
1	8	1	18	1	3
2	9	1	25	1	1,4
		2	24	1	4
		3	22	1	2
3	13	1	26	2	1,4
		2	11	3	3
4	6	1	14	1	3
		2	19	1	4
5	9	1	22	2	2,3
		2	25	1	2
6	10	1	16	1	4
		2	7	1	2,3,4
		3	21	1	1,2
7	12	1	19	1	2,3,4
		2	13	1	1,2,3
		3	23	3	4
8	13	1	25	1	1,2,3
		2	7	1	1,2
		3	24	3	1

There exist 8 jobs, which can be sequenced in 8! ways, all together 52,920 combinations of operation–machine allocation are possible for one of the job sequences (2×3×3×2×3×(3×2+1)×(3×3+1)×(3×2+1)). Hence, for 8! job sequences the total number of possible allocation turns out to be 52920×8! = 2,133,734,400. Some of these allocations are not possible because they are not able to satisfy system constraints such as available machining time. Enumerating an optimal/near optimal solution in such a huge search space is computationally complex. In this article, machine loading problem can be viewed as selecting a subset of jobs from the job pool and allocating them among machines. The objective considered is maximization of profitability based on maximization of throughput while satisfying the constraints, viz. available machining time. Furthermore, the unit profit of each throughput assumed to be 1 in this paper to make the results of the proposed model comparable with those reported for other methods in the literature. The proposed model has been tested on ten problems and the results are compared with solutions obtained by Modified Immune Algorithm reported in Prakash et al. [18]. Results show that the proposed model is very reliable and efficient.

The rest of the paper is organized as follows: Section 2 describes in detail the machine loading problem along with its modeling. Section 3 represents computational results to the proposed model and previous literature data provided for comparison the results. Finally, Section 4 concludes the paper.

2. Problem environment

2.1 Problem description

The FMS under consideration in this paper consists of a number of multifunctional CNC machines and tools with the potential to execute several operations, automated material handling devices and other amenities, where several types of jobs arrive with varied processing requirements. Jobs are available in batches and some of them are to be selected for processing during a given planning horizon. Job selection and loading constitute two major components of a tactical planning problem of any FMS.

The job selection problems are concerned with selecting the sets of jobs to be produced during the upcoming planning horizon while the loading problem involves allocation of operations.

A job includes one or more operations and each of them can be performed by one or more machines. The particularities related to the production requirement of the job, number of operations for each job and their machining time required by each operation of each job are known in advance. Essential and optional types of operations are allied with each job. Essential operations of a job means that this operation can be performed only on a particular machine whereas optional operations imply that they can be carried out on a number of machines with the same or varying processing time. In this problem, the flexibility lies in the selection of a machine for processing the optional operations of the jobs. The machine loading problem can be defined as "…given a set of jobs to be produced, using a set of resources such as material handling systems, pallets and fixtures, how the job be assigned so that some measures of productivity is optimized".

The complexity associated with machine loading problem has been discussed in the previous section. Due to such a large complexity, it is fairly difficult to evaluate the optimal solution of operation allocations on machines in the presence of several alternatives for the given problem.

Following assumptions and conditions must be satisfied for the formulation of the underlying problem.

- Any machine cannot perform more than one operation of the job at a time (in this version of the problem).
- Any job that is selected for processing on a certain machine must finish all its operations on a certain machine before considering the next job in sequence for that machine.
- Any particular operation of any job does not require more than one machine.
- Processing requirements of the jobs are known in advance.
- Sharing and duplication of tools is not considered.
- Loading/Unloading and transportation time is negligible.

In the following subsections, formulation of objective functions and constraints are discussed in detail.

2.2 Equations

The notations used to demonstrate the proposed model are shown below.

Subscripts
j index of job; j: 1,…, J
m index of machine; m:1,…, M
o index of operation; o: 1,…, O_j

Parameters
U_m under-utilized time on machine m
O_m over-utilized time on machine m
T_m time available on machine m
P_j unit profit of job j
b_j batch size of job j
t_{jom} time required by machine m for operation o of job j

Decision variables

$$x_{jom} = \begin{cases} 1 \text{ if operation o of job } j \text{ is assigned to machine } m, \\ 0 \text{ otherwise.} \end{cases}$$

$$y_j = \begin{cases} 1 \text{ if job } j \text{ is selected,} \\ 0 \text{ otherwise.} \end{cases}$$

2.3. Modeling the problem

The machine loading problem described above is formulated here as follows:

The objective is to maximize the throughput as formulated below:

$$\text{Max.} \quad \frac{\sum_{j=1}^{J} P_j b_j Y_j}{\sum_{j=1}^{J} P_j b_j}$$

Subject to the following constraints:

1- Over-loading and under-loading of machines are permitted. This can be expressed as:

$$\sum_{j=1}^{J}\sum_{o=1}^{O_j} b_j t_{jom} x_{jom} + U_m - O_m = T_m, \qquad \forall m \in 1,\ldots,M$$

2- The number of slots needed for the operations of the jobs to be performed on a machine must always be less than or equal to the tool slots available in that machine. This can be expressed as:

$$\sum_{j=1}^{J}\sum_{o=1}^{O_j} S_{jom}\, x_{jom} \leq S_m \ , \qquad \forall\, m \in 1,\ldots, M$$

3- Once a job is considered for processing, all the operations are to be completed before undertaking a new job (non-splitting of job), and once a machine is selected for an operation, it has to be completed on the same machine (unique job routing). This can be expressed as:

$$\sum_{m \in B(j,o)} X_{jom} = Y_j \ , \qquad \forall j \in 1,\ldots, J, \forall o \in 1,\ldots, O_j$$

4- Decision variables are binary. This can be expressed as:

$$x_{jom} = 0, 1 \quad y_j = 0, 1$$

5- Under-utilized and over-utilized times are non-negative:

$$U_m , O_m \geq 0$$

3. Results and Discussion

To be comparable with the literature, we assume $P_j = 1$ for all machines, i.e. the unit profit of each throughput assumed to be 1. The attempted model has been coded in Lingo Software.

Performance of the proposed model is evaluated based on some benchmark problems adopted from the literature [17]. The proposed model is tested on ten benchmark problems and the results are compared with those reported in Prakash et al. [18]. The solutions for ten problems are given in Table 2 and the comparative results are given in Table 3. From results, it can be seen that the proposed model performs better than the Modified Immune Algorithm (MIA) presented in [18].

Furthermore, for showing the robust of proposed model throughput of the system for all problems are taken account for comparison with those in the literature. Throughput refers to unit of job produced when all the jobs in a sequence is allowed for loading in the machine in the system. Figure 1 compares system unbalance (a) and throughput (b) obtained by different methods through a bar chart.

Table 2. Summary of results obtained by the proposed model.

Problem number	Jobs assigned	Jobs unassigned	Throughput
1	1,2,3,5,6,7	4	62
2	1,2,3,4,5,6	-	73
3	1,2,3,4,5	-	79
4	1,2,3,4,5	-	51
5	1,2,3,4,5,6	-	76
6	1,2,3,4,5,6	-	73
7	1,2,3,4,5,6	-	78
8	1,2,4,5,6,7	3	60
9	1,2,3,4,5,6,7	-	88
10	1,2,3,4,5,6	-	67

Table 3. Comparison of proposed model with the MIA

Problem number	Total number of jobs	MIA TH	MIA OFV	Proposed model TH	Proposed model OFV
1	8	48	0.43	62	0.58
2	6	63	0.59	73	0.76
3	5	69	0.71	79	0.86
4	5	51	0.57	51	0.57
5	6	61	0.52	76	0.81
6	6	61	0.57	73	0.82
7	6	63	0.56	78	0.80
8	7	44	0.28	60	0.69
9	7	-	-	88	0.84
10	6	56	0.69	67	0.75

4. Conclusions

Loading problem in a flexible manufacturing system is well known for possessing a large variety of objectives and constraints. The main contribution of this research is to develop an efficient mathematical programming model for solving the machine loading problem for a random FMS. The objective of the loading problem considered in this research is the maximization of throughput and so gaining maximum profit while satisfying the constraints, viz. available machining time. Some computational experimentation has been carried out to assess the effectiveness of the proposed model. Computational results indicate that the proposed model provides very promising solutions compared with those of Modified Immune Algorithm [18].

It should be pointed out that the proposed solution methodology uses a fixed, predetermined sequencing rather than using a sequencing rule or determining the optimum. To rectify this shortcoming, one can easily solve this problem by using various sequencing rules and then selecting the best solution. It is worth noting that application of the proposed model is limited to certain cases where there are sufficient number of jigs, fixtures, pallets and automated guided vehicles (AGVs) available in the shop floor. The work may be extended further by imposing constraints on the availability of these resources.

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