Computers & Industrial Engineering 101 (2016) 295–302

Contents lists available at ScienceDirect

Computers & Industrial Engineering

journal homepage: www.elsevier.com/locate/caie

Lagrangian approach to minimize makespan of non-identical parallel batch processing machines

Nurul Suhaimi, Christine Nguyen *, Purushothaman Damodaran

Department of Industrial & Systems Engineering, 590 Garden Road, EB230, Northern Illinois University, DeKalb, IL 60115, United States

ARTICLE INFO

Article history:
Received 13 July 2016
Received in revised form 14 September 2016
Accepted 17 September 2016
Available online 17 September 2016

Keywords:
Scheduling
Batch processing machines
Makespan
Lagrangian Relaxation approach

ABSTRACT

This research is motivated by the testing operations conducted at an electronics manufacturing facility. Printed Circuit Boards (PCBs) of varying size are assembled on multiple assembly lines. The PCBs from different assembly lines are later grouped to form batches that are scheduled for testing on non-identical Environmental Stress Screening (ESS) chambers. The ESS chambers can process multiple PCBs simultaneously as long as the total size of all PCBs in the batch does not exceed the chamber's capacity. The testing time of the batch depends on the composition of the batch. The chambers are referred to as Batch Processing Machines (BPMs) and PCBs are jobs in this paper. Scheduling non-identical BPMs to minimize the makespan objective is known to be NP-hard. Consequently, the Particle Swarm Optimization (PSO) and Random Keys Genetic Algorithm (RKGA) approaches were proposed in the literature. In this research, a Lagrangian Relaxation (LR) approach is proposed. The solution from the LR approach is compared to the solution from PSO, RKGA, and a commercial solver. An experimental study is conducted on benchmark instances and the LR approach identified a new improved solution for several problem instances.

1. Introduction

This research is motivated by a real life application in contract electronics manufacturing (i.e. an electronics manufacturer who assembles and tests Printed Circuit Boards (PCBs) which are used in consumer products). Environmental Stress Screening (ESS) chambers are used to test PCBs in order to detect early failures before they are used in the field. These chambers are capable of testing several PCBs concurrently. Hence, the chambers are equivalent to Batch Processing Machines (BPMs) and the PCBs are regarded as jobs in this research. The scheduler's responsibility is to form batches and schedule the batches on the chambers so that the completion time of the last batch is minimized. When the batches are formed, the composition of the batch determines the processing time of the batch. The batch processing time is equal to the job in the batch with the longest processing time. In electronics manufacturing, it is acceptable to test a job for longer than its prescribed testing time, however it will result in reducing the chamber's availability.

2. Problem description

The problem considered in this research is described as follows. For a set J of n jobs, $J = \{J_1, \ldots, J_n\}$, the jobs are grouped to form the batches, and the batches are then scheduled on a set M of q non-identical parallel batch processing machines, $M = \{M_1, \ldots, M_q\}$. The processing time of each job (p_j), size of each job (s_j) and each machine's capacity (S_m) are known. The maximum number of batches required to process all the jobs is easy to determine. Assuming one job per batch will result in n batches, hence, the maximum number of batches needed is also n. The batch processing time is equal to the longest processing time of all the jobs in the batch. The total size of all the jobs in the batch should not exceed the machine capacity in which it is processed. The objective function is to minimize the makespan (i.e. completion time of the last batch of jobs). In order to schedule the batch processing machines, two decisions need to be made. First, jobs need to be grouped into batches and second, the batches formed need to be scheduled. Both decisions are considered dependent on each other as the formation of the batch determines the batch processing time which then affects the makespan. The problem under study is known to be NP-hard (Damodaran, Diyadawagamage, Ghrayeb, & Velez-Gallego, 2012; Xu & Bean, 2007). Consequently, Damodaran et al. (2012) proposed Particle Swarm Optimization (PSO) and Xu and

* Corresponding author.
E-mail addresses: nmsuhaimi@gmail.com (N. Suhaimi), cnguyen@niu.edu (C. Nguyen), pdamodaran@niu.edu (P. Damodaran).

http://dx.doi.org/10.1016/j.cie.2016.09.018
0360-8352/

Bean (2007) proposed Random Keys Genetic Algorithm (RKGA) for the problem under study.

In this paper, a Lagrangian Relaxation approach for scheduling non-identical parallel batch processing machines to minimize the makespan is proposed. The effectiveness of the proposed approach is evaluated by solving benchmark problems from the literature and comparing the solution with other meta-heuristics (such as PSO and RKGA) previously published. An experimental study is also conducted to evaluate the solution quality by comparing the solution from the Lagrangian Relaxation approach with a commercial solver (i.e. IBM ILOG CPLEX). While heuristic and meta-heuristic solution approaches are known to have the best neighborhood search, the Lagrangian Relaxation (LR) approach is able to find the optimal solution either locally or globally (Raidl & Gruber, 2008).

The following assumptions, similar to the ones made in the real-life application and past literature (Damodaran et al., 2012; Xu & Bean, 2007), are made in this research:

1. All jobs in a batch will begin and end processing at the same time.
2. All jobs are available at time 0.
3. The machines do not fail.
4. Once a machine begins processing a batch, new jobs cannot be added to the batch and existing jobs cannot be removed from the batch.
5. When a machine completes processing a batch of jobs, the next batch can be immediately loaded with no setup time or delay due to operator unavailability.

3. Literature review

Potts and Kovalyov (2000) reviewed the literature on scheduling with batching decisions. The jobs are typically batched when they share the same setup on a machine or when the machine can process multiple jobs simultaneously. Most BPM scheduling literature minimize makespan and are classified as single or parallel BPM problems (Potts & Kovalyov, 2000). Uzsoy (1994) shows that scheduling a single BPM with non-identical job sizes to minimize total completion times and makespan is NP-hard. Lee and Uzsoy (1999) proposed polynomial and pseudo-polynomial time algorithms to minimize the makespan of a single BPM with dynamic job arrivals (i.e. job release times are not equal). The algorithm produced excellent results but had long computational times. Chandru et al. (1993) studied Branch-and-Bound (B&B) algorithms to minimize the total completion time or makespan in a single BPM. The set of jobs to be scheduled are grouped into families, where all jobs in the same family have the same processing time. Velez-Gallego, Damodaran, and Rodriguez (2011) proposed Modified Successive Knapsack Problem (MSKP) heuristics to minimize makespan in a single BPM under the assumptions of non-identical job sizes and non-zero job ready times. The heuristic outperformed other comparative approaches for test instances with 50 or more jobs.

Although scheduling parallel BPMs can be found in the literature, most of the literature was limited to identical BPMs with identical capacity. However, in non-identical BPMs the capacity of the machines vary. Ozturk et al. (2010) applied a classical bin packing heuristic to minimize the makespan of washing medical devices. The washers used to wash the Reusable Medical Devices (RMD) were considered as an identical parallel BPM. Damodaran, Velez-Gallego, and Maya (2011) considered Greedy Randomized Adaptive Search Procedure (GRASP) in minimizing makespan for parallel BPM in an electronics manufacturing company. The proposed GRASP approach outperformed other approaches. Damodaran and Velez-Gallego (2012) applied the Simulated Annealing (SA) algorithm to minimize the makespan and compared the results with GRASP in Damodaran et al. (2011). The proposed approach shows a comparable result to GRASP in terms of solution quality and computation time. The MSKP heuristic in Velez-Gallego et al. (2011) was extended by Damodaran and Velez-Gallego (2010) to identical parallel BPM and named it as Progressive Successive Knapsack Problem (PSKP). The heuristic aimed to minimize makespan with less computational time. Chang, Damodaran, and Melouk (2004) developed a Simulated Annealing algorithm for identical BPMs in parallel to minimize the makespan objective. The SA approach outperformed a commercial solver in most of the instances. Shao et al. (2008) proposed a neutral networks approach with a Master Weight Matrix to minimize the makespan with non-identical job sizes. The proposed approach was effective to solve large-scale problems when compared with other heuristics.

Xu and Bean (2007) proposed a Random Keys Genetic Algorithm (RKGA) to minimize makespan of non-identical BPMs. Their approach outperformed a solver used to solve the mathematical formulation. Damodaran et al. (2012) proposed a Particle Swarm Optimization (PSO) algorithm for the same problem studied in Xu and Bean (2007). They also simplified the mathematical formulation proposed in Xu and Bean (2007). The PSO algorithm also outperformed the RKGA approach. In this research, a Lagrangian Relaxation (LR) approach is proposed and the solution quality of LR is compared with PSO and RKGA approaches.

The first scheduling problem solved with LR approach was in 1975 by Muckstadt and Koenig when they applied the method to schedule a power generation system. They presented a mixed integer programming model to minimize the sum of unit commitment and economic dispatch costs subject to demand, reserve, generator capacity and generator schedule constraints. The Lagrangian method is used to decompose the problem by single generator and the sub-gradient method updates the Lagrange multipliers. Fisher (1981) stated that Lagrangian method is able to provide the best solution of any practical size for most scheduling or optimization problems. By dualizing the side constraints, the optimal solution of Lagrangian methods is either the lower bound (for minimization problems) or upper bound (for maximization problems) of the optimal value of the original problem (Fisher, 1981). In 1993, Luh examined practical solutions in three manufacturing scheduling problems. Each problem is formulated by adding and modifying constraints to increase the real world complexity. Again, LR is used to decompose the scheduling problems into job-level sub-problems. The sub-problem is easier to solve than the main problem and resulted in a near-optimal schedule. To reduce computation time, Luh and Hoitomt (1993) used Lagrange multipliers from the last schedule to initialize the multiplier in the next instance. Perdomo et al. (2006) applied the Lagrangian technique to solve surgery room operations problems. The approach minimized the completion time from assigning the patients to operating rooms and recovery beds. Velde (1990) presented the Branch-and-Bound algorithm for a two-machine flow shop problem to minimize the sum of the job completion times. LR provided the lower bounds for the problem. The algorithms outperformed the results from previous research. Chen, Chu, and Proth (1998) used Lagrange multipliers to relax the capacity constraints on machines. Instead of using the basic decomposition method on the relaxed problem to break the problem into job level sub-problem, they proposed a pseudo-polynomial time Dynamic Programming (DP) algorithm to prevent oscillation in the solution. Through LR, the algorithm found the optimal solution based on the “min-max” criteria for the job-shop scheduling.