Journal of Cleaner Production 148 (2017) 624–641

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

Integrated lot sizing and energy-efficient job shop scheduling problem in manufacturing/remanufacturing systems

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ARTICLE INFO

Article history:
Received 28 July 2016
Received in revised form
25 January 2017
Accepted 27 January 2017
Available online 1 February 2017

Keywords:
Capacitated dynamic lot sizing problem
Remanufacturing
Job shop
Energy-efficient scheduling
Relax-and-fix heuristic

ABSTRACT

In this paper, a system designed to produce multi-class single-level products through both manufacturing of raw materials and remanufacturing of return products is taken into consideration, with the aim of defining and solving an integrated lot sizing and energy-efficient job shop scheduling problem. A mixed-integer programming formulation is proposed for the problem. This model minimizes not only the manufacturing and remanufacturing costs, the setup cost and the inventory holding and backlogging costs over the planning horizon, but also the energy costs paid for the utilization of machines and the compression of processing times. Since the model is NP-hard, a relax-and-fix heuristic is proposed to solve the problem. The proposed algorithm is illustrated with a numerical example, and its performance is tested on a set of randomly generated experimental problems. The results show the efficiency of the algorithm. Besides, the performance of the proposed energy-efficient model has been compared with classical models (that consider only the minimization of manufacturing/remanufacturing, holding and setup costs); the results indicate that the proposed model not only diminishes the energy consumption and the machines idle times, but it actually reduces the overall cost of the system.

1. Introduction

Two of the problems that a production manager usually copes with in the management of a manufacturing company at the planning level are 1) the determination of the quantity of products to be manufactured at a given period with the objective of minimizing the total cost including production, holding and setup costs, and 2) the definition of the best resource allocation and the best starting and completion times of jobs with the goal of optimizing some criteria such as minimizing the makespan, maximizing the throughput, etc. (Urrutia et al., 2014). The first problem falls into the class of mid-term decision problems and is called lot sizing problem, whereas the second one belongs to the class of short-term decision problems and is called sequencing and scheduling problem. These two classes of decision problems are closely related since the output of the first (lot sizing) is the input of the second (sequencing and scheduling). However, in most of the production systems these problems are usually solved separately; in particular, the lot sizing is solved first to define the production targets and sequencing and scheduling problems are solved in the next step to meet the targets (Li and Ierapetritou, 2009). Such an approach does not always guarantee the feasibility of the obtained production plan, since most of the planning models take into account aggregate planning which may lead to overestimating or underestimating capacity (Wolosewicz et al., 2015). For this reason, the integration of lot sizing and sequencing/scheduling problems seems to be necessary.

In recent years, researchers have tried to model and solve several variants of integrated lot sizing and scheduling problems. In terms of time period terminology, these models fall into the categories of either big bucket or small bucket problems. Big bucket problems, are those where the time period is long enough to produce multiple items (in multi-item problem cases), while for small bucket problems the time periods are so short that only one item can be produced in each of them (Karimi et al., 2003). In big bucket problems, the system may contain single or multiple capacitated machines; in the latter case, the layout can be as parallel machines, flow shop, job shop, etc. Besides, the models may involve some other different features such as the characterization of the demand to be satisfied (it can be constant or vary over either regular or irregular periods) or the presence of setup costs and setup times,

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http://dx.doi.org/10.1016/j.jclepro.2017.01.166
0959-6526/

that can be fixed, or vary by product or be sequence-dependent. The details of such studies can be found in three survey papers appeared in the literature in the last two decades: categorizing the capacitated lot sizing and scheduling problems to big and small buckets, Drexl and Kimms (1997) present the mathematical formulations for different versions of these problems and review the relevant literature; Maravelias and Sung (2009) review the integration of medium-term production planning and short-term scheduling problems; they define the production planning problem and explain why integration with scheduling leads to better solutions; finally, Copil et al. (2016) introduce a classification scheme and discuss the development of different models of simultaneous lot sizing and scheduling problems over time in terms of the incorporation of additional constraints, the application of solution techniques and their potential application in industry.

Manufacturing plants are facing increasing pressure to reduce their undesirable impacts on environment (Zhang et al., 2017). For this reason, they are trying to substitute their old systems with sustainable ones with the aim of reducing wastes, energy consumption, carbon emissions, etc (Taticchi et al., 2015). Remanufacturing systems are among the efficient sustainable systems that are designed to decrease the amount of wastes sent to the environment by collecting the used products returned by the customers and transform them into new usable products through refurbishment, repair, upgrading (Teunter et al., 2006). From the mid-term production management point of view, as discussed before in connection with the traditional manufacturing systems, one of the problems that must be solved is the lot sizing problem. In this case, the objective is to determine not only the number of products manufactured but also the number of used products remanufactured in each time period, such that the total cost over the planning horizon is minimized. The integration of lot sizing and scheduling problems in remanufacturing systems is quite new. This may be due to the complexity of the problem in these systems in comparison to the same problem in manufacturing ones.

Recently, production firms try to decrease energy consumption of their systems in order to increase the sustainability (Shrouf and Miragliotta, 2015). By controlling the energy consumption, production companies will be able not only to decrease the amount of carbon emissions to the environment, but also to reduce the energy costs which have recently suffered a significant increase. One of the ways of obtaining such an efficiency in manufacturing environments is to address the production scheduling function by considering green metrics alongside the traditional performance indicators (May et al., 2015). The goal of this paper is to propose an approach to integrate lot sizing and job shop scheduling problem from the energy efficiency point of view, in an integrated manufacturing and remanufacturing system. We consider P classes of products to be produced in lots through both manufacturing of raw materials and remanufacturing of recovered used products in a job shop system over a discrete planning horizon of T big bucket periods. The given job shop system contains K different capacitated machines which consume certain amounts of energy when processing the products or when being idle. Besides, it is assumed that processing times of products on machines are controllable and can be compressed with additional energy costs. The objective is to determine the production plan and the sequence of the product lots on the machines so that both the production, holding, and setup costs and energy costs are minimized. To solve this problem, we present a mixed-integer programming (MIP) formulation which can be used to solve instances of limited size by means of commercial MIP solvers. Moreover, because of the complexity of the proposed model, an efficient relax-and-fix heuristic is developed to solve the large instances of the problem in a reasonable amount of time.

The original contributions of this paper are threefold:

- to the best of our knowledge, this is the first study that addresses the integrated lot sizing and job shop scheduling problem in manufacturing/remanufacturing systems and proposes a MIP formulation of this problem;
- we include in the objective function of the proposed MIP model new items taking into account energy efficiency, in order to design systems more effectively from the energy consumption point of view; according to our best knowledge, this is the first attempt to integrate dynamic lot sizing problems (DLSPs) with energy-efficient production scheduling problem in job shop environments;
- since the consideration of reverse flow of used products and the inclusion of energy-efficient terms in the objective function complicate the problem formulation significantly, we propose an effective MIP-based heuristic to solve the problem.

The paper is organized as follows. In the next section, the related literature is reviewed. In section 3, the problem is defined, and in section 4, the proposed mathematical formulation of the problem is reported and afterwards an illustrative example is given. In section 5, the relax-and-fix heuristic is presented. In section 6, we discuss the performance of the proposed heuristic in solving experimental problems. Finally, some conclusions are drawn in section 7 which also includes a description of future works.

2. Literature review

In this section, we briefly review the scientific literature relative to the integrated lot sizing and energy-efficient job shop scheduling problem in manufacturing/remanufacturing systems addressed in this paper. The relevant literature is classified into three categories: *dynamic lot sizing with product return and remanufacturing*, *energy-efficient production scheduling*, and *integrated lot sizing and job shop scheduling problems*.

2.1. Dynamic lot sizing with product return and remanufacturing

In the last five decades, several researches have been done on dynamic lot sizing and scheduling of manufacturing systems: besides the review in Drexl and Kimms (1997), in Jans and Degraeve (2008) a survey on meta-heuristic approaches for dynamic lot sizing problems is provided, whereas in Buschkhl et al. (2010) the authors classify and review the solution approaches for dynamic capacitated lot-sizing problems. However, few studies about lot sizing in remanufacturing systems, which is called lot sizing with product returns and remanufacturing (DLSPR), have been reported in the literature. According to our best knowledge, Richter and Sombrutzki (2000) and Richter and Weber (2001) are among the first researchers studying DLSPR. Richter and Sombrutzki (2000) address the Wagner and Whitin (1958) dynamic production planning and inventory control model in both pure remanufacturing and combined manufacturing/remanufacturing systems; they present mathematical formulations of the DLSP for these two classes of systems and modify the Wagner and Whitin (1958) algorithm to solve the problems. Richter and Weber (2001) extend the previous work of Richter and Sombrutzki (2000) by adding variable remanufacturing and manufacturing costs. Golany et al. (2001) studies the production planning of a single-item system with the option of remanufacturing in which the demand and the return rate are deterministic and the disposal option exists; an optimal solution approach is proposed for the problem when the costs are linear and the problem is proved to be NP-complete for a general concave cost. Beltran and Krass (2002) study DLSP with