Computers & Operations Research 59 (2015) 33–50

Contents lists available at ScienceDirect

Computers & Operations Research

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

Unequal individual genetic algorithm with intelligent diversification for the lot-scheduling problem in integrated mills using multiple-paper machines

Marcos Furlan [a,b], Bernardo Almada-Lobo [b], Maristela Santos [a], Reinaldo Morabito [c,*]

[a] Instituto de Ciências Matemáticas e de Computação, Universidade de São Paulo, Av. Trabalhador São-carlense 400, São Carlos 13560-970, Brazil
[b] INESC-TEC, Faculdade de Engenharia, Universidade do Porto, Rua Dr. Roberto Frias s/n, Porto 4200-465, Portugal
[c] Departamento de Engenharia de Produção, Universidade Federal de São Carlos, Rod. Washington Luís KM 235, São Carlos 13565-905, Brazil

ARTICLE INFO

Available online 3 January 2015

Keywords:
Genetic algorithm
Diversification mechanism
Pulp and paper industry
Multi-stage lot-sizing and scheduling problem
Parallel machines

ABSTRACT

This paper addresses the lot-sizing and scheduling problem of pulp and paper mills involving multiple paper machines. The underlying multi-stage integrated production process considers the following critical units: continuous digester, intermediate stocks of pulp and liquor, multiple paper machines and a recovery line to treat by-products. This work presents a mixed integer programming (MIP) model to represent the problem, as well as a solution approach based on a customized genetic algorithm (GA) with an embedded residual linear programming model. Some GA tools are explored, including literature and new operators, a novel diversification process and other features. In particular, the diversification process uses a new allele frequency measure to change between diversification and intensification procedures. Computational results show the effectiveness of the method to solve relatively large instances of the single paper machine problem when compared to other single paper machine solution methods found in the literature. For multiple paper machine settings, in most runs the GA solutions are better than those obtained for the MIP model using an optimization software.

1. Introduction

The pulp and paper industry is a high-capital productive sector of, mostly, large mills that can produce pulp, paper or both in an integrated fashion. This complex production system can be viewed as a multi-stage problem that combines some critical units in single or multiple production lines. These critical units may have limited resources which are expensive to enlarge in order to avoid production bottlenecks. For that reason, it is necessary to efficiently use those resources. Furthermore, there are different pulp and paper mill layouts and a wide range of items produced, ranging from standard paper to special pulps used to produce textiles, for example. Because of the complexities involved in these industrial settings, it is difficult to determine effective production plans for most companies in this sector, requiring problem description generalizations, elaborate mathematical models and novel solution approaches.

A pulp and paper mill basically consists of: the pulp digester, which produces virgin pulp using a thermochemical, chemical or mechanical process to extract the pulp from the wood; the paper machine, which produces paper of different characteristics to meet customer demands; the recovery plant, which recovers the production residual and produces steam, electric energy and some components used in pulp extraction in the case of chemical processes; and the intermediate stocks of pulp and liquors, which allows higher autonomy between consecutive production units in case of breaks and production exchanges.

The pulp and paper lot-sizing and scheduling problem aims at improving the use of the production resources in order to, for example, minimize variable production costs or maximize contribution margins and profits. Some production characteristics and restrictions should be considered and ensured in the developed production plans. The aim is to define the lot sizes and their production sequence during a pre-defined multi-period planning horizon, considering customer demands, resource limits and other characteristics such as production rates, setup costs and setup times in each period.

Various papers studying different planning problems associated with the pulp and paper industry can be found in the literature, such as using surplus steam for district healing [1,2], lot-sizing problems associated with paper machines [3], production problems integrating lot-sizing and cutting decisions in the paper machines [4,5] and integrated lot-sizing and scheduling problems [6,7]. As the focus of the present study is on problems coupling lot-sizing and scheduling

* Corresponding author. Tel.: +55 16 3351 9516.
E-mail addresses: mafurlan@icmc.usp.br (M. Furlan), almada.lobo@fe.up.pt (B. Almada-Lobo), mari@icmc.usp.br (M. Santos), morabito@ufscar.br (R. Morabito).

http://dx.doi.org/10.1016/j.cor.2014.12.008
0305-0548/

decisions, some related papers which have tackled these integrated problems are described in more detail below.

For instance, [6] studied the integrated problem in a Portuguese pulp and paper mill and proposed a MIP-based heuristic to solve it. The authors considered three sub-plants of the company: the pulp plant, the paper plant and the recovery plant. The solutions of the method provide detailed production plans for the entire mill. Ref. [7] studied the same integrated problem in [6], but considered two additional characteristics: production cycles in the production sequence of the paper machine and backlogging within these production cycles. A VNS approach was developed to solve the problem and its performance was compared to the previous MIP-based heuristic and an optimization solver. These papers addressed multi-stage mills with one resource per stage, that is, a single digester which continuously feeds a single paper machine.

This paper has two main purposes. The first is to extend previous mathematical formulations to cope with production processes which have multiple production lines, as found in other pulp and paper companies. This work focuses particularly on some Brazilian mills with multiple paper machines competing for raw material, such as virgin pulp. In these production processes, the digester feeds multiple paper machines and sends the by-product to a single recovery line. The pulp and by-product intermediate stock levels should be controlled during the production process. These mills pose additional production planning challenges which are not addressed in previous papers.

Synchronization between consecutive productive processes is necessary to enable intermediate inventory control. In [6], this control was performed in sub-period changes since the authors consider no variation in the production flow during each sub-period. Sub-periods are smaller parts of a period as, for example, production shifts or smaller periods of time. The model presented in Section 3 adopts the same assumption. However, a new challenge arises to solve that assumption due to the multiple paper machines. The quantity of sub-periods is increased to maintain the flexibility between lot sizes and machine schedules. This way, the number of sub-periods per day is at least equal to the number of shifts multiplied by the number of machines. The growth in the number of sub-periods associated with the minimum lot size requirements easily creates infeasibility situations, which means that it is difficult to ensure the minimum lot sizes as the quantity of sub-periods grows. To overcome this difficulty, the minimum lot-sizing constraints were rewritten, even allowing null sub-periods when the produced paper grammage does not change. In order to avoid speed changes in the digester during tiny or null sub-periods, a new set of constraints was included to define the minimum sub-period size and allow speed variation.

The second main purpose of this paper is to present a novel solution approach based on genetic algorithm (GA) to solve the pulp and paper lot-sizing and scheduling problem with multiple paper machines. GA became popular after the pioneering work by [8]. Several variants of the original GA have been proposed in different areas of the literature over the last decades. Basically, a GA consists of an initial population (set of solutions) and selection, crossover and mutation operators. A comprehensive survey of GA was presented by [9], where important characteristics of GA were discussed. Ref. [10] reviewed different papers applying GA to solve lot-sizing problems. The authors discussed GA and problem characteristics, and classified the literature papers according to these aspects. Some examples of recent studies applying GA to solve lot-sizing problems are found in [11–18].

The proposed GA contains some special structures to solve this problem. For example, the decode and genetic operators are based on rules of this specific problem, which can be adapted and extended to similar cases. Furthermore, as part of this work a diversification mechanism was developed to introduce some variability throughout the search. Sometimes the convergence process is premature in GA, depending on the selection pressure, type of individual replacement, shape of the solution space, among other factors. This issue is overcome by the alternative diversification procedure. Another feature presented in GA is the process of adjusting the number of sub-periods of each individual. Adjusting this number is a difficult task and quite often that quantity is overestimated. The idea here is to adjust this value through the generations, allowing the use of individuals with a different number of sub-periods in the same population. Furthermore, this work also investigates the benefits of using larger initial populations and some hot-start solutions (solutions constructed based on specific heuristics or rules).

The method presented here is a hybrid approach, which uses an LP solver to provide the best linear programming solution for each integrated scheduling pattern (individual). Methods combining meta-heuristics and exact methods in combinatorial optimization have already been used in the literature, yielding good results. For example, a genetic algorithm with mathematical programming techniques embedded in was successfully applied to a two-level lot sizing and scheduling problem arising from the soft drink industry [18]. These and other papers have demonstrated successfully the advantages of combining metaheuristics with mathematical programming to solve real-world problems. According to [19], this method fits into an integrative combination by incorporating an exact method (LP model) in a meta-heuristic (GA).

This paper is organized as follows: the pulp and paper lot-sizing and scheduling problem characteristics are described in detail in Section 2 and a mathematical model for the multiple paper machine case is presented in Section 3. The proposed GA is described in Section 4 and the problem data and computational results are presented in three parts in Section 5. Firstly, the best GA variant is chosen by combining each feature developed/used in this paper. Secondly, the best variant is compared to single machine approaches of the literature for solving single machine problem instances, and then to the MIP solver Cplex for solving multiple machine problem instances. Thirdly, additional computational tests are presented and analyzed considering different runtime limits for a subset of multiple paper machines instances. Finally, in Section 6 conclusions are drawn and some topics for future research are suggested.

2. Problem definition

As illustrated in Fig. 1, this paper considers the pulp and paper production process. This representation is based on the problem considered by [6], where the mill is divided into three different plants. The pulp plant consists of the digester, the associated recycled pulp mill and the tanks of pulp. The paper plant is composed of the parallel paper machines, the winders and the reels (intermediate stocks of big paper rolls called jumbos). The recovery plant includes the evaporator, the tanks of black liquor, the recovery boiler and the energy turbines to transform surplus steam into electric energy. The function of each unit is briefly presented below.

- Pulp plant:
  - The digester produces the virgin pulp and the black weak liquor as a by-product (see Fig. 1). Two types of thermo-chemical digesters can be observed in the mills: continuous production and batch production. Continuous digesters are bigger and their production is controlled by changing the digester speed, the amount of chemicals introduced and the temperature. This study addresses a continuous digester and some industrial practices, as in [6].