Computers & Operations Research 60 (2015) 67–78

Contents lists available at ScienceDirect

Computers & Operations Research

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

Hybrid approach for buffer allocation in open serial production lines

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ARTICLE INFO

Available online 11 February 2015

Keywords:
Buffer allocation problem
Combinatorial optimization
Hybrid meta-heuristics
Production lines

ABSTRACT

The buffer allocation problem is an NP-hard combinatorial optimization problem involving the determination of the number of buffers in buffer locations required to increase the efficiency of a production line. Researchers in this field have proposed various optimization techniques to solve the problem for different types of production system configurations. In this study, a hybrid approach-based simulation optimization is proposed to determine the buffer sizes required in open serial production lines to maximize the average production rate of the system. This approach involves the use of a search tool and an evaluative tool. A hybrid approach using a genetic algorithm and simulated annealing is used as a search tool to create candidate buffer sizes. As an evaluative tool, discrete event simulation modeling is used to obtain the average production rate of the line. The performance of the proposed approach and the power of the hybridization are investigated for various serial line configurations. Promising results demonstrate the efficacy of the proposed hybrid approach for the buffer allocation problem in open serial lines.

1. Introduction

Efficient management of buffer size allocation is a key concern in production systems. The basic structure of allocation involves a decision regarding how much buffer storage is available and where to place it within the production line to improve the production system. This problem is called the buffer allocation problem (BAP) in the literature and is widely recognized by production systems designers. Buffers can significantly improve the capacity of a line by reducing the effects of stochastic interference due to breakdowns or variations in processing times. Allocating buffers between workstations allows the workstations to operate more independently from each other [1]. The buffers help to reduce the starving (no input available)-blocking time (no space to dispose of output) and smooth the production flow to increase the efficiency of a line. However, allocating buffers into a production line is costly and may be inadequate due to the floor space in the system. If the buffers are too large, both the direct costs through capital costs and indirect costs through increased WIP inventory and the cycle times will outweigh the benefits of increased productivity. If the buffers are too small, the servers will be underutilized or the demand will not be met [2].

In the relevant literature, BAPs have been studied for many years because they contribute to the improvement of the overall performance of a system. For a systematic classification of relevant studies on BAPs in various production systems, the interested reader can refer to comprehensive surveys by Dallery and Gershwin [3], Papadopoulos and Heavey [4] and Demir et al. [5]. In this context, because the focus of this study is on the BAP in serial production lines, contemporary studies are considered relevant.

Approaches to solving the BAP can be based on design rules or heuristics that can assist the decision maker in selecting good buffer configurations without undertaking complex analysis or numerical algorithms for selecting optimal/near-optimal buffer allocations, as indicated by Harris and Powell [6]. The most prominent studies on the design rules or heuristics for the BAP include Freeman [7], Conway et al. [8], Hillier and So [9,10], Dallery and Gershwin [3], Powell [11], Powell and Pyke [12], Hillier [13], Papadopoulos and Vidalis [14], Chan and Ng [15], Enginarlar et al. [16,17] Hillier and Hillier [18] and Staley and Kim [19]. Numerical algorithms developed for the BAP involve search (generative) algorithms and evaluative algorithms that are deployed in an iterative manner [20,21]. In this respect, the evaluative method is used for predicting the performance measures of a given system. In the BAP literature, simulation [6,22–27], the aggregation method [28–30], the generalized expansion method [31], traditional Markov state models [32], decomposition methods [1,2,20,33–42] and the segmentation method [43] are used as evaluative tools. Search algorithms are employed to search for an optimal/near-optimal buffer configuration moving from an existing candidate solution. Dynamic programming [30,44], nonlinear programming [40], gradient-based search methods [2,34,36], Spendley–Hext- and Nelder–Mead-based simplex search algorithms [6], the degraded ceiling method [39], and

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http://dx.doi.org/10.1016/j.cor.2015.01.009

meta-heuristics such as simulated annealing [20,27,31,35], tabu search [1,22,27,41,42], genetic algorithms [20,27–29], and ant colony optimization [38] are examples of search methods employed for the BAP in serial production lines.

To increase the performance of the aforementioned approaches based on meta-heuristics, a recent trend observed in the literature is to hybridize the meta-heuristics to solve any production problem. Although many studies have focused on solving the BAP, the studies in which hybrid meta-heuristic approaches are proposed to solve the BAP are still very limited. These approaches include nested partitions [45], branch and bound methods [29] and line search [46].

In this study, we propose a simulation optimization approach based on the hybrid genetic annealing algorithm (GAA), which is a hybridization of the genetic algorithm (GA) and simulated annealing (SA), to solve the BAP in serial lines. The GAA yields candidate buffer configurations, and a discrete-event simulation model thereby evaluates the production rate of a serial line with each of the candidate buffer configurations. The motivation behind the hybridization is to combine the strengths of individual pure meta-heuristics and achieve top performance in solving the BAP. While exploiting the power of GA to obtain candidates in different areas in the search space, SA possesses better convergence properties that can help to improve the solution. Although the idea of hybridizing GA with SA has been proposed for solving many production problems (*e.g.*, scheduling problems [47–49], machine loading problems [50] and tool-path planning problems [51]), to the best of our knowledge, this study represents the first attempt to solve the BAP in serial lines by using the hybrid GAA.

The remainder of this paper is organized as follows. The next section explains the BAP in serial lines and various conditions associated with serial lines. The proposed hybrid solution approach and its implementation are described in Section 3. Experimental studies are presented in Section 4. Finally, the last section provides concluding remarks and presents future research directions.

2. Buffer allocation problem in serial lines

The BAP is a difficult, stochastic, integer, non-linear, NP-hard and combinatorial optimization problem [32]. In serial production lines, there are W workstations connected in series and $W-1$ buffer stages between the related workstations, as shown in Fig. 1. Material flows from outside the system to W_1, then to B_1, then to W_2, and so forth until it reaches W_w, after which it leaves [52]. In open production lines, the first workstation on the line is never starved and the last workstation is never blocked. The main objective is to maximize the average production rate of the line subject to a given total buffer capacity. The mathematical formulation of BAP can be expressed as follows:

$$\text{Find} \quad B=(B_1, B_2, \ldots, B_{W-1}) \quad \text{to} \tag{1}$$

$$\max \quad f(B) \tag{2}$$

subject to

$$\sum_{i=1}^{W-1} B_i = K \tag{3}$$

$$B_i \geq 0 \tag{4}$$

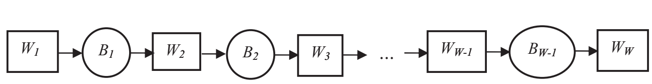

Fig. 1. A serial production line with buffers [53].

$$B_i \text{ non}-\text{negative integers } (i=1,2,\ldots,W-1) \tag{5}$$

where W is the number of workstations in the line, K is a non-negative integer representing the total buffer size in the system allocated among the $W-1$ buffer locations, B represents the buffer vector, and $f(B)$ represents the average production rate of the system under a given buffer configuration.

Complete enumeration is the exact solution method for finding the optimal buffer sizes for this problem. However, the number of feasible allocations of K buffer slots among $W-1$ buffer locations increases dramatically with K and W. Hence, complete enumeration is not an appropriate tool for solving a BAP in large-sized production lines. Therefore, researchers widely adopt various optimization methods to solve BAPs effectively.

In this study, we focused on average production rate maximization in open serial production lines considering various cases involving different system requirements, such as variations in processing times, workstation breakdowns and limitations of buffer stages. A production line for which the mean processing times are equal at all workstations is called a balanced line. On the other hand, in unbalanced lines, workstations can have different processing times, and one or more bottleneck workstations may exist, whose mean processing time is longer than other workstations. Reliable lines usually involve human operators who are not subject to breakdowns but whose processing times show significant variability [6]. On the other hand, in unreliable lines, workstations operate with constant processing times and fail randomly, leading to breakdowns of significant duration. Therefore, large buffer sizes are required to keep the unreliable line running during breakdowns. However, there can be upper bounds on the number of buffers allocated in the buffer locations due to the limitations of a facility's location. The proposed hybrid approach, which will be implemented in various cases of a serial line, is explained in Section 3.

3. Proposed hybrid approach

Because of the combinatorial nature of optimal buffer allocation, optimal solutions can generally be determined only for short production lines. For larger lines, meta-heuristics have recently been used as efficient search tools to solve combinatorial optimization problems. The proposed simulation optimization approach based on the hybrid genetic annealing algorithm (GAA) combining meta-heuristics of GA and SA has been introduced for solving the BAP.

GA is an iterative method that consists of a constant-size population of individuals encoding a possible solution in a search space for the problem. An initial population of individuals (or initial solution) is determined randomly. In each step, the current population is improved by forming a new population (or new candidate solution) using the best properties of the current population according to predetermined quality criteria, *e.g.*, fitness function. Unlike most conventional methods and certain meta-heuristics (*e.g.*, SA, tabu search), which conduct a single directional search, GA performs multiple directional searches by using a set of candidate solutions [54]. Although they do not guarantee optimality, the searches often find a near-optimal solution. GA-based approaches have been presented in the BAP literature [20,28,29,55–58].

SA is a stochastic neighborhood search method developed for combinatorial optimization problems. It was initially proposed by Kirkpatrick et al. [59] based on the analogy to the annealing of solids. The SA algorithm has the capability of jumping out of local optima for global optimization. This capability is achieved by accepting probability neighboring solutions worse than the current solution. The acceptance probability in the algorithm is determined by a temperature control parameter, which decreases during the SA procedure.