G Model
JMSY-589; No. of Pages 20

ARTICLE IN PRESS

Journal of Manufacturing Systems xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Journal of Manufacturing Systems

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

Technical Paper

Mixed-model U-shaped assembly lines: Balancing and comparing with straight lines with buffers and parallel workstations

Lorenzo Tiacci [1]

Università degli Studi di Perugia – Dipartimento di Ingegneria, Via Duranti, 93, 06125, Perugia, Italy

ARTICLE INFO

Article history:
Received 22 February 2017
Received in revised form 17 July 2017
Accepted 18 July 2017
Available online xxx

Keywords:
Genetic algorithm
U-line
Mixed-model
Unpaced lines
Asynchronous lines
Buffer allocation
Stochastic task times
Discrete event simulation

ABSTRACT

In the paper a genetic algorithm approach is proposed to balance asynchronous mixed-model U-shaped lines with stochastic task times. U-shaped lines have become popular in recent years for their ability to outperform straight assembly lines in terms of line efficiency. The great majority of studies in the literature deal with paced synchronous U-shaped lines. Asynchronous lines can be more efficient than synchronous lines, but are more difficult to study, due to blocking and starvation phenomena caused by the variability of completion times: this makes it difficult to calculate the effective throughput. This variability, that in straight lines comes from the stochastic nature of task times and from the changing of models entering the line, is even higher in U-shaped lines, where an operator can work at two different models in the same cycle at the two sides of the line. For this reason, the genetic algorithm proposed is coupled to a parametric simulator for the evaluation of the objective function, which contains the simulated throughput. Two alternative chromosomal representations are tested on an ample set of instances from the literature. The best solutions are also compared with the best solutions known in the literature, on the same instances, for straight lines with buffers and parallel workstations. From the comparison it turns out that U-shaped lines are generally more efficient with respect to straight lines with buffers. This is because crossover work centers naturally act similarly to unitary buffers, providing two places in which two loads can be placed simultaneously. The superiority of U-shaped lines holds true as long as it is possible to take full advantage of the employment of crossover work centers. For particular types of instances, depending on the distribution of task times, this possibility decreases, so that straight lines with parallel workstations and buffers are preferable.

1. Introduction

The purpose of this paper is twofold. The primary objective is to present a genetic algorithm approach to balance asynchronous mixed-model U-shaped lines with stochastic task times. The secondary objective is to draw some general managerial insights about the efficiency of U-shaped lines versus straight lines with parallel workstations and buffers.

U-shaped assembly lines differ from straight lines because a worker can process loads on both sides of the U-line. As depicted in Fig. 2b, a work center (WC) may consist of one worker working at two sides of the line. These types of WCs, named 'crossover' work centers, are the advantage of U-shaped lines with respect to straight lines. Indeed, the tasks assignable to a crossover work center, without violating precedence constraints, increase with respect to a work center in a straight lines. As a consequence, finding more balanced line configurations become possible. It is also noteworthy that every solution feasible for straight lines is feasible for an U-line, because an U-line does not need to include crossover WCs.

The U-shaped assembly line balancing problem (U-ALBP) has been formulated for the first time by Miltenburg and Wijngaard [1] as an extension of the classic Assembly Line Balancing Problem (ALBP) related to straight lines. The problem is to assign tasks to work centers while respecting precedence constraints. On the basis of different objectives, the problem can be classified in three 'types': minimization of the number of stations for a given cycle time (Type I), minimization of the cycle time for a given number of stations (Type II), maximization of Line Efficiency (Type E). The Line Efficiency (LE) is defined as the ratio between the sum of all task times and the product between number of stations and the cycle time. In Type E problems both the number of stations and the cycle time are not imposed. If the cycle time is imposed, maximizing LE is equivalent to minimizing the number of stations.

Most research on mixed-model U-shaped lines deals with deterministic task times, as it will show in the literary review (Section 2). Furthermore, despite it is certainly an argument that the unpaced

E-mail address: lorenzo.tiacci@unipg.it
[1] Web-site: www.impianti.dii.unipg.it/tiacci.

http://dx.doi.org/10.1016/j.jmsy.2017.07.005
0278-6125/

Please cite this article in press as: Tiacci L. Mixed-model U-shaped assembly lines: Balancing and comparing with straight lines with buffers and parallel workstations. J Manuf Syst (2017), http://dx.doi.org/10.1016/j.jmsy.2017.07.005

line is preferable and truer to realistic work environment [2], most research is still focused on the paced, both for straight and for U-shaped lines. In paced lines the cycle time of all stations is equal to the same value *ct*, all stations begin with their operations at the same point in time and also pass on workpieces at the same rate. As a consequence, all station times of a feasible balance may never exceed *ct*, as otherwise the required operations could not be completed before the workpiece leaves the station. An unpaced line, on the contrary, is not strictly restricted by a cycle time. Instead, it advances when stations have completed their tasks. Unpaced lines can be: synchronous, if all stations pass on their workpieces simultaneously (after all stations have completed their tasks); asynchronous, if each station decides on transference individually.

One of the reasons why the literature on asynchronous unpaced lines is very limited is that these lines are more difficult to study. This is due to blocking and starvation phenomena caused by the variability of completion times, which makes difficult to calculate the effective throughput. In straight lines there can be two reasons for which task times can vary: if task times are stochastic or if different models are assembled in the line. The same reasons are valid also for U-shaped lines, but the variability of completion times is expected to further increase, because the same operator can work at two different models in the same cycle at the two sides of the line.

Being very difficult to calculate the effective throughput both of a straight and of an U-shaped asynchronous line, researchers have so far developed methods to seek station assignments that lead to balanced workloads across stations and across products, with the motivation to limit the effect, on the realized cycle time, of the variation of task times. This has been achieved by searching for the maximization/minimization of some measures of 'vertical' and 'horizontal' balancing/variability. For example, the Smoothness Index (SI) is a measure of 'vertical' balancing, i.e. of the workload equalization among stations, measuring the deviation of workloads from the maximum station time. The 'Workload Variation' (WV) is a measure of vertical variability, representing the deviation of station workloads from the average station workload, and works similarly to SI: both are used in order to provide the equalization of the workloads among stations. The Absolute Deviation of Workloads (ADW) is a measure of 'horizontal variability', i.e., of the variation of task times within each station. These types of workload smoothing objectives have been substantially utilized, instead of throughput, because the throughput of a mixed model line is difficult to estimate, while measures related to workload smoothing, for given tasks assignments, can be calculated straightforwardly. But using workload smoothing as objective, as outlined by Karabati and Sayin [3], remains an approximate approach, especially for unpaced asynchronous lines.

Recently, the implementation of parametric object-oriented simulators for assembly lines, which allow to accurately estimate the throughput of complex line configurations in a very fast and flexible way [4], opened to the possibility to efficiently balancing asynchronous lines. This is possible as these simulators are so fast and flexible that can be embedded in algorithms and procedures where thousands of different line configurations have to be evaluated and compared in terms of their effective throughput. The genetic algorithm presented here-in takes advantage of this recent development to solve for the first time the stochastic version of the Mixed Model U-shaped Assembly Line Balancing Problem (MMULBP) specifically for asynchronous unpaced lines. In the paper two alternative chromosomal representations are presented and tested on an ample set of instances from the literature.

As far as the secondary objective of the paper is concerned, it is well known that U-shaped lines outperform simple straight lines. This superiority is basically due to the possibility to find more balanced line configurations. As already mentioned, being an operator able to work at the two sides of the U line, the number of tasks that are potentially assignable to an operator without violating precedence constraints increases, so that precedence constraints are in some way relaxed. However, straight lines provide the possibility to implement paralleling, i.e. to set parallel workstations performing the same task set. This possibility allows not only to perform tasks with processing time larger than the desired cycle time, but also to enlarge the solution space of the problem, so that feasible and potentially better balanced configurations can be found [5]. Furthermore, the possibility to use buffers between WCs is supposed to provide additional benefits in terms of performances, so that the superiority of U-shaped lines without buffers with respect to straight lines with parallel WSs and buffers between WCs is not indisputable, and has still to be demonstrated. The aim of the paper, from this side, is to compare U shaped asynchronous lines with respect to Asynchronous Straight Lines with Parallel workstations and Buffers within work centers (ASLPB). This is done by comparing the best U-shaped solutions found by the genetic algorithm presented here-in with the best ASLPB solutions found so far in the literature on the same instances. Although this comparison rests on the current 'state-of-the art' balancing capabilities, it is possible to drawn some interesting managerial insights of general validity.

The paper is organized as follows. In Section 2 a detailed literary review on the U-shaped assembly line balancing problem is presented. Then, in Section 3, the problem to solve is formalized, in terms of description of the underlying U-shaped line model and of problem constraints and objectives. Section 4 is devoted to the description of the proposed genetic algorithm approach. In Section 5 the design of experiment is presented, and related results are discussed in Section 6.

2. Literature review

Papers dealing with the U-shaped assembly line balancing problem can be classified considering two important features, which characterize the problem itself: the number of model entering the line (single model or mixed model) and the task completion times (deterministic or stochastic). Four subsections of the literary review are dedicated to consider all the combinations of these two features: single model/deterministic tasks; single model/stochastic tasks; mixed model/deterministic tasks; mixed model/stochastic tasks. Table 1 shows an overall scheme of the papers in this field, and reports the adopted methodology, the objectives of the problem, and other possible characteristics of the problem. A further section is finally devoted to summarize the advances brought by the present work with respect to the existing literature.

2.1. Single model, deterministic task times

The U-shaped line balancing problem has been formulated for the first time by Miltenburg and Wijngaard [1], that also showed how the solution techniques for the traditional line balancing problem could be adapted for use with the new problem. Urban [6] formulated the U-line line balancing problem as integer program. Scholl and Klein [7] proposed a branch and bound procedure for balancing U shaped lines, named ULINO, and applied it to solve Type I, II and E problems. Erel et al. [8] proposed a heuristic that consists of two main parts: a solution generator, able to generate a new solution from the old solution by relaxing the cycle time constraint, and a Simulated Annealing (SA) module, that takes the solution from the first step and attempts to obtain a feasible allocation while minimizing the maximum station time. The global objective is to find feasible solutions with the lower number of stations. Baykasoglu [9] presented a multiple objective SA algorithm for simple and U