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Robust assembly line balancing with heterogeneous workers

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A B S T R A C T

Assembly lines are manufacturing systems in which a product is assembled progressively in workstations by different workers or machines, each executing a subset of the needed assembly operations (or tasks). We consider the case in which task execution times are worker-dependent and uncertain, being expressed as intervals of possible values. Our goal is to find an assignment of tasks and workers to a minimal number of stations such that the resulting productivity level respects a desired robust measure. We propose two mixed-integer programming formulations for this problem and explain how these formulations can be adapted to handle the special case in which one must integrate a particular set of workers in the assembly line. We also present a fast construction heuristic that yields high quality solutions in just a fraction of the time needed to solve the problem to optimality. Computational results show the benefits of solving the robust optimization problem instead of its deterministic counterpart.

1. Introduction

Assembly lines are flow-oriented systems that rely on the division of work. The operations needed to assemble a given product are assigned to different workstations, and this assignment must respect technical constraints, such as precedence relations between tasks. In its basic form, the resulting optimization problem is known as the *simple assembly line balancing problem* (SALBP) and its two most common variants consist in minimizing the number of workstations needed while ensuring a given productivity level (problem of type I) or maximizing productivity with a fixed number of workstations (problem of type II). The reader interested in the SALBP is referred to Baybars (1986), Scholl (1999), Scholl and Becker (2006), Becker and Scholl (2006), Boysen, Fliedner, and Scholl (2007, 2008), Battaïa and Dolgui (2013), and Sivasankaran and Shahabudeen (2014).

One of the main assumptions of the SALBP is that task execution times are worker-independent. This assumption is relaxed in the *assembly line worker assignment and balancing problem* (ALWABP), where one must simultaneously assign both tasks and workers to stations. Our interest in the ALWABP is motivated by its application to the management of assembly lines in sheltered work centers for the disabled (SWDs) (Miralles, García-Sabater, Andrés, & Cardos, 2007). Since the original study of Miralles et al. (2007), the ALWABP has received a considerable amount of attention. The problem has been tackled by means of heuristics (Blum & Miralles, 2011; Chaves, Lorena, & Miralles, 2009; Moreira & Costa, 2009; Moreira, Ritt, Costa, & Chaves, 2012; Mutlu, Polat, & Supciller, 2013) and exact algorithms (Borba & Ritt, 2014; Miralles, García-Sabater, Andrés, & Cardos, 2008; Vilà & Pereira, 2014). In addition, several authors have studied variants of the problem with features such as job rotation schedules, mixed-model production, parallel stations or worker collaboration (Araújo, Costa, & Miralles, 2012, 2015; Cortez & Costa, 2015; Costa & Miralles, 2009; Moreira & Costa, 2013). It is worth noting that most of these studies have considered problems of type II, which are relevant in the context of SWDs which usually aim to provide work experience to as many workers with disabilities as possible.

In many types of decision problems, deterministic models are inadequate and uncertainty should be taken into account explicitly in the optimization model so as to properly represent real-life situations. In the case of assembly lines, uncertainty is often present in task execution times and arises from a series of factors such as the unpredictability and variability in work rates, as well as in skill and motivation levels (Becker & Scholl, 2006). In the management of SWDs, these variations can be very significant due to the high heterogeneity of the workers and to their lack of prior work experience. Learning effects or successive improvements to the line are sometimes modeled by means of dynamic task times, which use

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fuzzy numbers with known membership functions (e.g. Boucher, 1987; Toksarı, İşleyen, Güner, & Baykoç, 2010; Zacharia & Nearchou, 2012). Other studies consider stochastic task execution times under some probability distributions. For more details, see Suresh and Sahu (1994), Nkasu and Leung (1995), Sotskov, Dolgui, and Portmann (2006), Özcan (2010), Fazlollahtabar, Hajmohammadi, and Es'aghzadeh (2011), Özcan, Kellegöz, and Toklu (2011), Gurevsky, Battaïa, and Dolgui (2012, 2013).

Robust optimization (Gabrel, Murat, & Thiele, 2014) is a popular approach for the handling of uncertainty when the probability distribution of the uncertain parameters is unknown. Here we assume that only an interval of possible values for each task execution time is available. We adopt a budget-of-uncertainty robustness approach as proposed by Bertsimas and Sim (2003, 2004), which has been successfully applied to a large variety of problems (Alem & Morabito, 2011; Bertsimas & Thiele, 2006; Hazır, Erel, & Günalay, 2011; Lu, Ying, & Lin, 2014; Moon & Yao, 2011; Solyalı, Cordeau, & Laporte, 2012). According to this paradigm, the combined scaled increase of uncertain parameters from their nominal values is limited by a budget, as will be seen in the following section. Hazır and Dolgui (2013) have proposed a robust approach for the SALBP of type II by including an uncertainty budget on each station, and have solved the resulting problem by means of a Benders decomposition algorithm. Gurevsky, Hazir, Battaïa, and Dolgui (2013) have considered a robust SALBP of type I which was solved by branch-and-bound.

In this paper, we extend the approaches for the SALBP developed by Hazır and Dolgui (2013) and Gurevsky, Hazir et al. (2013) to the ALWABP. We focus on the problem of type I, following the framework proposed by Moreira, Miralles, and Costa (2015) in which the ALWABP is extended beyond the context of SWDs to that of conventional assembly lines. There, the goal is to integrate a set of workers with disabilities in a conventional assembly line while minimizing the number of extra stations needed, resulting in the *assembly line worker integration and balancing problem* (ALWIBP).

This paper makes four main scientific contributions. We first introduce the *robust assembly line worker assignment and balancing problem* with the objective of minimizing the number of workstations (RALWABP-1). We then describe two formulations for the general problem and we explain how these formulations can be adapted to handle the integration of a set of heterogeneous workers (RALWIBP-1). Thirdly, we propose a fast heuristic for the RALWIBP-1 which yields high quality solutions within short computing times. Finally, we show that solving the robust problem leads to much better solutions compared to solving its deterministic counterpart.

The remainder of the paper is organized as follows. In Section 2, we provide a formal definition of the problem and we introduce our two mathematical models. This is followed by a description of the heuristic in Section 3, and by the results of computational experiments in Section 4. Finally, Section 5 ends the paper with some conclusions and avenues for future research.

2. Problem description and formulations

Let $S = \{1, \ldots, m\}$ be a an ordered set of workstations, $W = \{1, \ldots, o\}$ a set of workers, with $|W| = |S|$, and $N = \{1, \ldots, n\}$ a partially ordered set of tasks. The partial order on the tasks can be defined by an acyclic precedence graph $G = (N, E)$, where arc $(i, j) \in E$ indicates that task i is an immediate predecessor of task j. We also define the graph $G^* = (N, E^*)$ as the transitive closure of G, i.e., there exists an arc $(i, j) \in E^*$ whenever there is a path from i to j in G. In addition to the above definitions, we use the following notation:

$t_{wi} \in \mathbb{N}^* \cup \{\infty\}$	time of task $i \in N$ when executed by worker $w \in W$;
$W_i = \{w \in W : t_{wi} \neq \infty\}$	set of workers who are able to execute task $i \in N$;
$N_w = \{i \in N : w \in W_i\}$	set of tasks that worker $w \in W$ is able to execute;
$D_i = \{j \in N : (j, i) \in E\}$	set of immediate predecessors of task $i \in N$;
$D_i^* = \{j \in N : (j, i) \in E^*\}$	set of all predecessors of task $i \in N$;
$F_i = \{j \in N : (i, j) \in E\}$	set of immediate successors of task $i \in N$;
$F_i^* = \{j \in N : (i, j) \in E^*\}$	set of all successors of task $i \in N$.

Given a fixed productivity rate, associated with a cycle time $\bar{c}$, the aim of the ALWABP-1 is to determine an assignment of tasks to workers minimizing the number of stations required while respecting precedence relationships. In this study, we assume that the task execution times are uncertain and have unknown probability distributions. We consider, however, that the execution times are independent of each other and that the execution time of task i by worker w belongs to the interval $[\bar{t}_{wi}, \bar{t}_{wi} + \hat{t}_{wi}]$, where $\bar{t}_{wi}$ is the nominal value and $\hat{t}_{wi}$ is the maximum deviation from $\bar{t}_{wi}$.

Sections 2.1 and 2.2 present two RALWABP-1 formulations adapted from Borba and Ritt (2014) and Moreira et al. (2015), respectively. Although the model of Miralles et al. (2007) can also be adapted to handle uncertainty, preliminary tests have shown that finding feasible solutions to its robust counterpart is extremely hard, even for moderate size instances. For this reason, we do not consider it in this study. Section 2.3 considers the special case of the RALWIBP-1.

2.1. A robust model based on the formulation of Borba and Ritt (2014)

Borba and Ritt (2014) introduced an ALWABP-2 formulation that considers the assignment of tasks to workers and the relative position of the workers in the assembly line. Let x_{wi} be a binary variable equal to one if and only if task $i \in N$ is assigned to worker $w \in W$, and d_{vw} be a binary variable equal to one if and only if worker v precedes worker w. In order to modify their model for the type-I problem, we introduce binary variables z_w equal to one if and only if worker w is assigned to the assembly line. We also define parameter $\bar{c}$ as the maximum allowed cycle time in the line. The modified model is the following:

$$M1: \text{ minimize } \sum_{w \in W} z_w \tag{1}$$

subject to

$$\sum_{w \in W_i} x_{wi} = 1 \qquad i \in N \tag{2}$$

$$\sum_{i \in N_w} \bar{t}_{wi} x_{wi} \leqslant \bar{c} \qquad w \in W \tag{3}$$

$$d_{vw} \geqslant x_{vi} + x_{wj} - 1 \qquad (i,j) \in E, \quad v \in W_i, \quad w \in W_j \setminus \{v\} \tag{4}$$

$$d_{uw} \geqslant d_{uv} + d_{vw} - 1 \qquad \{u, v, w\} \subseteq W; \quad |\{u, v, w\}| = 3 \tag{5}$$

$$d_{vw} + d_{wv} \leqslant 1 \qquad v \in W, \quad w \in W \setminus \{v\} \tag{6}$$

$$\sum_{i \in N_w} x_{wi} \leqslant |N_w| z_w \qquad w \in W \tag{7}$$

$$x_{wi} \in \{0, 1\} \qquad w \in W, \quad i \in N_w \tag{8}$$

$$d_{vw} \in \{0, 1\} \qquad v \in W, \quad w \in W \setminus \{v\} \tag{9}$$

$$z_w \in \{0, 1\} \qquad w \in W. \tag{10}$$

The objective function (1) minimizes the number of stations by minimizing the number of workers assigned to the assembly line. Constraints (2) ensure that each task is executed by one worker.