Assembly Line Worker Integration and Balancing Problem

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Abstract

We propose the Assembly Line Worker Integration and Balancing Problem (ALWIBP), a new assembly line balancing problem arising in lines with conventional and disabled workers. The goal of this problem is to maintain high productivity levels by minimizing the number of workstations needed to reach a given output, while including in the assembly line a number of disabled workers. This problem gains importance in the current social context, where companies are urged to integrate disabled workers in their labour force. Our results indicate that not only can these workers be integrated with little effect on the lines productivity but also that additional companies goals can be simultaneously considered.

Keywords: Assembly line balancing; disabled workers; mathematical modeling.

1 Introduction

According to the International Labour Organization (ILO), people with disabilities represent an estimated 10 per cent of the world's population, or some 700 million people worldwide, where approximately 500 million are of working age; being apparent that in all countries the unemployment rates of the disabled are much higher than the average.

Employment is the main path for social inclusion and participation in modern societies. Having a job is not only the basis for the survival and stability for many individuals, but also the key for the access to many rights as citizens. Therefore the welfare and the social inclusion of the disabled depend very much on the degree of labor integration they are able to achieve. Different active policies to combat the discrimination have been set during the last decades, following models that are more/less inclusive depending on local culture. Across specific national legislations, a general common formula is to reserve a share of workplaces in ordinary companies for people with disabilities. This share normally increases with the size of the company and, depending on the country legislation, usually goes from 2% to even 5% of the jobs.

Unfortunately, it is also a common phenomenon in many countries that this share is not always achieved, and very often companies try to avoid it somehow. Therefore it is clear that the solution should come not only by legal imposition, but mainly by overcoming the prejudices about the capabilities of the disabled, and by the genuine commitment of ordinary companies to include integration programs in their strategies. Thus, the aim of this paper is to contribute to overcome these prejudices, making easier this commitment: 1) by providing the production managers with practical approaches that ease the integration of disabled workers in the production lines; 2) by demonstrating how, through the approaches proposed, the productivity of production systems suffers very little (and many times none) decrease.

1.1 Assembly lines as a tool for integration: ALWABP review

Once stated the great importance of integrating Disabled into the workforce of ordinary companies, this section will start with a brief introduction on some previous work inspired on the specific scenario of the so-called "Sheltered Work Centres for Disabled" (henceforth SWDs).

SWDs are a special work formula legislated in many countries (with different variants) whose only difference from an ordinary company is that most of its workers (normally around 70%) must be disabled, and therefore they receive some institutional help in order to be able to compete in real markets. This labor integration formula has been really successful in decreasing the former high unemployment rates of countries like Spain, and one of the strategies used by SWDs to facilitate the labor integration has been the adoption of assembly lines. In this sense, Miralles et al. (2007) were the first to evidence how the integration of disabled workers in the productive systems can be done without losing, even gaining, productive efficiency through the use of assembly lines. This pioneer reference defined the so-called Assembly Line Worker Assignment and Balancing Problem (ALWABP); a configuration initially inspired in the heterogeneous scenario of SWDs assembly lines, where workers normally execute the tasks at different rates, and where the division of work into single tasks seems to be a powerful tool for making certain worker disabilities invisible.

Since (Miralles et al.; 2007), many other references have contributed to give visibility to ALWABP throughout our academic area, proposing different methods to solve the problem. The same authors have later developed a branch-and-bound algorithm for the problem, enabling the solution of small-sized instances (Miralles et al.; 2008). Because of the problem complexity and the need to solve larger instances, the literature has since then shifted its efforts to heuristic methods. The current state-of-the-art methods for solving the ALWABP are the iterated beam search (IBS) metaheuristic of Blum (2011) and the biased random-key genetic algorithm of Moreira et al. (2012).

1.2 Contribution and outline of this work

ALWABP was inspired in the SWDs reality, where the very high diversity of most of the workers and their limitations are the main characteristics. This scenario is quite different to the one of an ordinary company; where the aim is to efficiently integrate in the workforce just some workers to cope with the 2% to 5% of disabled workers legislation requirements. In this case the problem supposes much less diversity in the input data, and can also be stated with very different approaches with respect to the ALWABP, regarding the objective function, the hypothesis and the model defined, and the kind of procedures most useful in this new scenario.

The aim of this paper is to present a model and analyze this new problem that has been named “Assembly Line Worker Integration and Balancing Problem” (ALWIBP). Our study aims to answer specific requirements that normally arise in assembly lines of ordinary companies, where only few disabled workers have to be integrated, providing the production managers with practical tools that ease the integration of disabled workers in the most efficient manner. In fact, as the social conscience and implication of companies increase, this consideration of heterogeneity should become a normal question in production planning issues.

The remainder of this paper is structured as follows: in Section 2, we state a formal codification of the new problem and some extensions, analyzing their practical implications and reviewing those references of the literature with useful related approaches. Section 3 then presents the corresponding IP models for all proposed versions of the ALWIBP while Section 4 proposes a experimental study in order to analyze the effectiveness of the proposed models. General conclusions end this manuscript.

2 The Assembly Line Worker Integration and Balancing Problem

2.1 Introduction: SALBP vs ALWABP

The so-called Simple Assembly Line Balancing Problem (SALBP) was initially defined by Baybars (1986) through several well-known simplifying hypotheses. This classical single-model problem, which consists of finding the best feasible assignment of tasks to stations so that certain precedence constraints are fulfilled, has been the reference problem in the literature in its two basic versions: when the cycle time C is given, and the aim is to optimize the number of necessary work stations, the problem is called SALBP-1. Whereas when there is a given number m of workstations, and the goal is to minimize the cycle time C the literature knows this second version as SALBP-2 (Scholl; 1999).

A trend of Assembly Line researchers in the last decade has been to narrow the gap between the theoretical proposals and the reality of industrial assembly lines. In this sense the initial reference of Miralles et al. (2007) is part of this trend, properly defining the Assembly Line Worker Assignment and Balancing Problem from the observation of the SWDs real assembly lines specifications. Thus, ALWABP is a generalization of SALBP where, in addition to the assignment of tasks to stations, a set of heterogeneous workers also has to be assigned to stations. In this scenario each task has a worker-dependent processing time, which allows taking into account the limitations and specific production rates of each worker. The input data are normally expressed by a precedence network and a time matrix, where for every task several operation times are possible depending on the worker. Moreover, when the time to execute a task for certain worker is very high, this assignment is considered infeasible in the input data matrix.

2.2 ALWIBP definition

The ALWABP problem was inspired in the SWDs reality with most workers presenting a high diversity of operation times; whereas the ALWIBP scenario introduced in section 1.2 pretends to simulate the "desirable" situation of (initially) just some 5-10% of disabled workers being integrated in a conventional assembly line. As stated in the literature review of section 1.1., the main (and only studied) approach when talking about disabled integration in assembly lines has been ALWABP-2 (Miralles et al.; 2008; Moreira et al.; 2012, e.g.), since the typical objective in SWD is to be as efficient as possible with the (diverse) available workforce.

In the scenario associated with the ALWIBP, it makes sense to deal with the type 1 problem: since the basic aim of a production manager can be to integrate the normative (common in most countries) 5% of disabled workers into the assembly line, or even some (most desirable) 10% of them; while maintaining a given production rate. The objective in this scenario is to ensure this production rate while at the same time: (1) integrating the given disabled workers (in some cases some 5% of workers, in other cases even more than 10% whether some compensation is needed due to low shares in other factory sections); and (2) minimizing the number of additional workstations.

In addition to these basic objectives, we define two extensions to the ALWIBP-1 (see sections 3.2 and 3.3) regarding the desired position of the bottleneck/s and the way the idle time is spread out in the workstations. In this sense two clear preferences can be important secondary objectives for a production manager:

- once we minimize the total number workstations, inside the solution subspace with minimal number of workstations, the manager may aim to find that assignments in which the idle time of stations with disabled workers is minimum, in order to increase their participation in the production process (see ALWIBP-1S$_{min}$ in section 3.2).
- or the opposite: in some contexts the manager may prefer to avoid any disabled worker with the responsibility of becoming bottleneck. In this case, a given idle time (slack) can be imposed, as new constraints, to workstations to which disabled workers are assigned (see ALWIBP-1S$_{sl}$ in section 3.2).

In the following, we propose integer linear models for the basic ALWIBP-1 situation and also for the two extensions exposed.

3 Mathematical models

In this section, we present mathematical models for the ALWIBP defined earlier. Several variants will be presented, all of them relating to the basic problem formally described as follows: let N be the set of tasks to be assigned and $G = (N, E)$ an acyclic precedence graph where each eage $(i, j) \in E$ indicates a precedence that must be respected. The following additional notation is used:

S	set of workstations;
W	set of disabled workers, $\|W\| \leq \|S\|$;
t_i	execution time of task i when assigned to a conventional worker;
t_{wi}	execution time of task i when assigned to a disabled worker $w \in W$;
$I_w \subseteq N$	set of unfeasible tasks for worker $w \in W$;
$P_i = \{j \mid (j,i) \in E\}$	set of immediate predecessors of task i;
$F_i = \{j \mid (i,j) \in E\}$	set of immediate successors of task i.

As mentioned earlier, we consider the type 1 version of the ALWIBP: given a fixed cycle time $\overline{C}$, find an assignment of tasks minimizing the number of workstations such that all disabled workers are integrated and precedence constraints are respected. In the following, we propose linear models for this problem.

3.1 ALWIBP-1

The formulation of ALWIBP-1 follows the idea used by Petterson and Albracht (1975) when modeling the SALBP-1. Let q be an artificial task and $D_q = \{i \in N | F_i = \varnothing\}$ be the set of tasks that do not have followers. We assume that all tasks in D_q precede task q and that the execution time of task q is always 0, i.e., $t_q = t_{wq} = 0, \forall w \in W$. Using a modified set of tasks $N' = N \cup \{q\}$, we can write the ALWIBP-1 model as:

$$\text{Min} \sum_{s \in S} s x_{sq} \tag{1}$$

subject to

$$\sum_{s \in S} x_{si} = 1, \qquad \forall i \in N', \tag{2}$$

$$\sum_{s \in S} y_{sw} = 1, \qquad \forall w \in W, \tag{3}$$

$$\sum_{w \in W} y_{sw} \leq 1, \qquad \forall s \in S, \tag{4}$$

$$\sum_{s \in S | s \geq k} x_{si} \leq \sum_{s \in S | s \geq k} x_{sj}, \qquad \forall i,j \in N' | i \in P_j, k \in S, k \neq 1, \tag{5}$$

$$\sum_{i \in N'} t_i \cdot x_{si} \leq \overline{C}, \qquad \forall s \in S, \tag{6}$$

$$\sum_{i \in N' \setminus I_w} t_{wi} \cdot x_{si} \leq \overline{C} + L_w(1 - y_{sw}), \qquad \forall s \in S, \forall w \in W, \tag{7}$$

$$y_{sw} \leq 1 - x_{si}, \qquad \forall s \in S, \forall w \in W, \forall i \in I_w, \tag{8}$$

$$\sum_{s \in S | s \geq k} y_{sw} \leq \sum_{s \in S | s \geq k} x_{sq}, \qquad \forall w \in W, \forall k \in S | k \neq 1, \tag{9}$$

$$x_{si} \in \{0,1\}, \qquad \forall s \in S, \forall i \in N', \tag{10}$$

$$y_{sw} \in \{0,1\}, \qquad \forall s \in S, \forall w \in W. \tag{11}$$

where:

x_{si}	binary variable equals to one if task $i \in N'$ is assigned to workstation $s \in S$,
y_{sw}	binary variable equals to one if a disabled worker $w \in W$ is assigned to workstation $s \in S$,
L_w	large constant, $w \in W$.

The objective function minimizes the index associated with the last station (the one that executes the fictitious last task q). In association with constraints (3) which state that all disabled workers are assigned, this objective function minimizes the number of conventional workers used in the line. Constraints (4) garantee that each workstation receives at most one (disabled) worker. Constraints (2) ensure that all tasks are assigned, while constraints (5) guarantee that the precedence relations are respected. These inequalities were proposed by Ritt and Costa (2011) which analysed several versions of precedence constraints and concluded that constraints (5) presented the better theoretical and practical results. Constraints (6) and (7) ensure that the cycle time is respected at stations without and with disabled workers, respectively. The constant L_w must be sufficiently large to deactivate these last constraints if $y_{sw} = 0$. Therefore, we take $L_w = \sum_{i \in N \setminus I_w} |t_{wi} - t_i|$. This expression assumes the maximum additional time that a disabled worker must spend at a station, in comparison to a conventional worker This would be the additional time associated with the execution all feasible tasks.

Finally, constraints (8) and (9) guarantee that disabled workers are not assigned to tasks which they are not able to execute and that they execute at least one task, respectively.

3.2 ALWIBP-1S$_{min}$

The ALWIBP-1S$_{min}$ is characterized by the addition of another term in the objective function related to the idle time of the disabled workers. The new goal is to hierarchically minimize the number of stations (with higher priority) and the idle time of the stations with disabled workers. Thereby, this version of the problem aims to obtain more balanced solutions that increase the participation of these workers in production.

To model this situation, we use non-negative real variables $\delta_s, \forall s \in S$, and $\delta_w, w \in W$, to measure the idle time at each station s with a conventional worker and at each station with disabled worker w. For convenience, we assume that $\delta_s = 0$ if a disabled worker is assigned to station s. The values of these new variables are obtained with the aid of slack variables $l_s, \forall s \in S$ and $l_{sw}, \forall s \in S, \forall w \in W$ associated to constraints (6) and (7), which are rewritten as:

$$\sum_{i \in N'} t_i \cdot x_{si} + l_s = \overline{C}, \qquad \forall s \in S, \tag{12}$$

$$\sum_{i \in N' \setminus I_w} t_{wi} \cdot x_{si} + l_{sw} = \overline{C} + L_w(1 - y_{sw}), \qquad \forall s \in S, \forall w \in W, \tag{13}$$

and with new constraints which are added to establish the correct relations between δ_s, δ_w and the slack variables:

$$\delta_s \geq l_s - \left(\sum_{i \in N'} p_i\right) \cdot \sum_{w \in W} y_{sw}, \qquad \forall s \in S, \tag{14}$$

$$\delta_w \geq l_{sw} - (1 - y_{sw}) \cdot \left(L_w + \sum_{i \in N'} p_i\right), \qquad \forall s \in S, \forall w \in W. \tag{15}$$

Note that constraints (14) and (15) define the idle time of workstations with conventional and disabled workers, respectively. The objective function can now include terms associated with the idle times, as stated below:

$$\text{Min} \sum_{s \in S} sx_{sq} + \sum_{w \in W} \frac{\delta_w}{\overline{C}|W|} \tag{16}$$

subject to

$$\begin{aligned} (2)-(5), (12)-(15), (8)-(9),& \\ (10)-(11),& \\ l_s \in \mathbb{R}_+, &\quad \forall s \in S, && (17)\\ l_{sw} \in \mathbb{R}_+, &\quad \forall s \in S, \forall w \in W, && (18)\\ \delta_s \in \mathbb{R}_+, &\quad \forall s \in S, && (19)\\ \delta_{sw} \in \mathbb{R}_+, &\quad \forall s \in S, \forall w \in W. && (20) \end{aligned}$$

The constant term multiplying the idle time variables imposes a hierarchical characteristic in the objective function, giving priority to the minimization of stations and using the idle times as a secondary objective.

3.3 ALWIBP-1S$_{sl}$

The ALWIBP-1S$_{sl}$ approach establishes a minimum idle time to be imposed in workstations to which disabled workers are assigned. This problem arises in contexts in which it is desirable that disabled workers do not occupy bottlenecks in assembly lines (in order to facilitate integration, e.g.) Note that this objective is contradictory to the one presented earlier in the ALWIBP-1S$_{min}$, and is obviously applied in distinct situations.

The formulation of this problem is presented below:

$$\text{Min} \sum_{s \in S} sx_{sq} \tag{21}$$

subject to

$$\begin{aligned} (2)-(5), (12)-(13), (8)-(9),& \\ (10)-(11), (17)-(18),& \\ l_{sw} + \left(L_w + \sum_{i \in N'} p_i\right) \cdot (1 - y_{sw}) \geq sl, &\quad \forall s \in S, \forall w \in W. && (22) \end{aligned}$$

where:
sl minimum idle time on workstations with disabled workers.

4 Experimental study

4.1 Justification of a new ALWIBP benchmark

As discussed in section 2, the ALWABP was inspired in SWDs where the very high diversity of workers and their limitations are the main characteristics; whereas the ALWIBP scenario described above pretends to simulate the "desirable" situation of only some 5-10% of disabled workers being integrated in conventional assembly lines. Moreover, as stated earlier, the main (and only studied) approach in this scenario has been ALWABP-2, since the typical objective in SWD is to be as efficient as possible with the (diverse) available workforce. Instead, in this new scenario, the ALWIBP-1 approach is realistic, since the basic aim of a production manager can be to integrate the normative (common in most countries) 5% of disabled workers into the assembly line, or even some (most desirable) 10% of them; while maintain a given productivity. Therefore the benchmark generation scheme should also include a "desirable cycle time" associated with a given productivity that must be ensured. The objective, therefore, is to reach this cycle time while: (1) integrating the given disabled workers; and (2) also minimizing the number of additional workstations.

Many previous proposals for ALWABP-2 were evaluated with the set of 320 benchmark instances first proposed by Chaves et al. (2009). Once stated the completely different scenario where ALWIBP arises, it is clear that this classical ALWABP benchmark is not useful here since, as explained above: (1) only a little share of the workers are disabled; and (2) the basic aim is now to minimize workstations of non-disabled workers (ALWIBP-1 perspective). As the sub-space of possible optimal solutions is large, we can even combine this primary aim of minimizing conventional workstations with other secondary problem characteristics such as the minimization of idle times associated with stations with disabled workers (ALWIBP-1S_{min}) or the ensuring that disabled workers are not assigned to bottleneck stations (ALWIBP-1S_{sl}).

Therefore a new ALWIBP benchmark is necessary to objectively test our proposals, where for every new instance generated: only little shares of disabled workers must be created; and a realistic and comparable "desirable cycle time" must be defined a priori (ALWIBP-1 perspective).

4.2 ALWIBP benchmark scheme

As many other ALB approaches, the ALWABP benchmark was constructed from the only SALBP reference (the Scholl data collection of www.assembly-line-balancing.de); that was considered robust enough and has been extensively used to test most proposals in the literature so far. But it happens that, as recently demonstrated by Otto et al. (2011), this framework does not seem rigorous enough. The problems were collected from different empirical and not empirical sources, and are based only on 25 precedence graphs; where just 18 distinct graphs have more than 25 tasks and thus are meaningful for comparing solution methods. Otto et al. (2011) also point out the triviality of some of these benchmark problems: for more than 57% of the instances an optimal solution was found by at least one of the 10,000 runs of a simple random search. Moreover, for 44 instances (16% of the data set), the share of optimal solutions in the solution space exceeds 90%. Even 24 problem instances appeared to be trivial, because all the solutions found in 10,000 runs of a random search with constructive evaluation were optimal.

To avoid these two inconvenient, and somehow related, characteristics of the benchmark (which is: low diversity of graphs structure, and triviality), Otto et al. (2011) proposed a SALBP generator and a new very robust challenging benchmark whose graphs morphologies include a sufficient variety of chains, bottlenecks and modules. Basically, they propose different cells of data sets (with 25 different instances per cell) following a full-factorial design for the following parameters:

- number of tasks ("small", "medium", "large" and "very large")

- type of the graph (with graphs containing more chains, or more bottlenecks, or "mixed")
- Order Strength ("low" , "medium" and "high")
- distribution of task times ("peak at the bottom", "bimodal", and "peak in the middle").

Thus, to generate our ALWIBP benchmark, we selected as basis the following subset from the Otto et al. (2011) benchmark:

1. Following their advice, we use the "medium" data subset (with $n = 50$ tasks) for testing our models with exact approaches.
2. From them, we consider that diversity of graphs is sufficiently ensured selecting only the instances of the "mixed" subset (that have both bottlenecks and chains) with low and high Order Strength.
3. In what concerns distribution of task times, we then select only the "peak at the bottom" and "bimodal" subsets. Since we need to compare our best solution integrating disabled workers with that of the corresponding SALBP instance, we discard the "peak in the middle" subset because the optimal number of stations is unknown for almost the half of the instances.

For the whole benchmark the instances are classified from "less tricky" to "extremely tricky" and it happens that, the four cells finally selected have a quite symmetric composition regarding the triviality; which is very important.

Thus, we generated our benchmark of "medium" ALWIBP problems from this base of 100 selected SALBP "medium" ($n = 50$) instances in the following way: from each of these 100 instances we respect the precedence network and the conventional task time, and then we generate four different instances by adding one only disabled worker with: high or low variability of task time respect to the original ones, and high or low percentage of incompatibilities. The two levels defined for the task times variability used the distributions $U[t_i, 2t_i]$ and $U[t_i, 5t_i]$ for low and high variability, and the low and high percentage of incompatibilities in the tasks-workers matrix was set to 10% and 20% approximately. Following the same scheme we created 400 additional instances by creating two workers, then three workers, and finally four workers. Therefore, in total the benchmark has 1600 "medium" instances with the structure described.

4.3 ALWIBP experimentation

For the experimental study, the input cycle time is always set to 1000 as this is a matter of normalizing the time units only. Furthermore, as Otto et al. (2011) states, this value seems to be large enough to flexibly generate a wide range for the time variability ratio and further time structure measures.

4.3.1 Experiment 1: ALWIBP-1

One basic aim of every company should be to integrate at least the normative percentage of disabled workers into the workforce. In this experimental study, we aim to demonstrate that the proposed methods enable the inclusion of higher percentages of disabled workers in the line without important losses in productivity.

Productivity always means somehow (output result / input resources involved) and in this case productivity can be defined as (cycle time / number of workstations). As the cycle time is always fixed in 1000 time unities, an increase on the number of workstations means a decrease of productivity.

In order to check what would be the shape of this expected loss of productivity, we compared the solutions of the 100 selected SALBP "medium" (n=50) instances from Otto et al. (2011) benchmark with our solutions when (applying the model in section 2.1) we integrate consecutively one, two, three and four workers. As explained above there are 400 instances for every case, with every set including workers with more and less variability and more and less percentage of incompatibilities and also diversity in graphs morphology. The overall results are shown in Table 1:

$\|W\|$	Var	Inc	Δ	$t(s)$	$m_\uparrow$	$m_\uparrow(\%)$	τ
1	$U[t_i, 2t_i]$	10%	96	24.4	0.2	2.8%	145.2
		20%	97	23.2	0.2	2.9%	131.1
	$U[t_i, 5t_i]$	10%	93	47.1	0.4	5.1%	230.4
		20%	92	51.0	0.4	5.5%	238.5
2	$U[t_i, 2t_i]$	10%	95	34.6	0.4	4.6%	96.3
		20%	95	35.8	0.4	4.6%	100.7
	$U[t_i, 5t_i]$	10%	92	55.1	0.7	8.5%	134.4
		20%	94	39.9	0.7	8.6%	138.7
3	$U[t_i, 2t_i]$	10%	95	37.8	0.5	6.1%	64.7
		20%	90	64.8	0.6	6.7%	81.8
	$U[t_i, 5t_i]$	10%	92	64.2	1.1	13.4%	120.9
		20%	89	74.0	1.2	14.1%	129.8
4	$U[t_i, 2t_i]$	10%	87	85.4	0.7	8.1%	56.7
		20%	84	108.0	0.8	9.4%	72.5
	$U[t_i, 5t_i]$	10%	90	91.7	1.5	17.0%	101.9
		20%	88	119.3	1.5	18.0%	111.7

Table 1: Computational results concerning the ALWIBP-1 model.

In this table and in the following ones, the columns indicate: $|W|$: number of disabled workers; Δ: the number of instances solved to optimality in 600s of computation; $t(s)$: computational time (on average); $m_\uparrow$: number of worstations increased (on average); $m_\uparrow(\%)$: percentage of the number of worstations increased (on average); τ: idle time of stations with disabled workers (on average).

As expected, the increase in the number of stations increases with the number of disabled workers to be integrated and with the variability of the task times. Nevertheless, it can be observed that even in the most constrained case (4 disabled workers with execution times of up to 5 times the conventional time and 20% incompatibility), an average of only 1.5 new stations had to be added to integrate the workers.

4.3.2 Experiment 2: ALWIBP-1S$_{min}$ and ALWIBP-1S$_{50}$

As the sub-space of possible ALWIBP-1 optimal solutions is large, we can combine this primary aim of minimizing conventional workstations with other secondary (important) objectives as stated in the definition of the following ALWIBP extensions:

1. To also minimize the idle time of disabled workers: ALWIBP-1S$_{min}$;
2. To ensure that every disabled worker must have a given slack respect to bottleneck station: ALWIBP-1S$_{50}$.

In the first case we try to minimize the idle time while minimizing the number of stations. In the second case we impose additional constraints to the ALWIBP which avoid any disabled

$\|W\|$	Var	Inc	Δ	$t(s)$	$m_\uparrow$	$m_\uparrow(\%)$	τ
1	$U[t_i, 2t_i]$	10%	98	15.5	0.2	2.6%	1.8
		20%	98	14.3	0.2	2.9%	3.1
	$U[t_i, 5t_i]$	10%	90	71.1	0.4	5.1%	9.5
		20%	91	56.0	0.4	5.5%	10.0
2	$U[t_i, 2t_i]$	10%	89	80.2	0.4	4.5%	1.9
		20%	89	78.7	0.4	4.4%	3.4
	$U[t_i, 5t_i]$	10%	80	137.4	0.7	8.5%	6.9
		20%	81	146.9	0.7	8.6%	8.8
3	$U[t_i, 2t_i]$	10%	87	115.0	0.5	6.3%	2.6
		20%	85	121.0	0.6	6.8%	3.4
	$U[t_i, 5t_i]$	10%	70	224.8	1.2	13.9%	7.4
		20%	68	235.9	1.3	14.6%	11.1
4	$U[t_i, 2t_i]$	10%	66	278.5	0.8	8.7%	3.7
		20%	68	258.2	0.8	9.5%	5.1
	$U[t_i, 5t_i]$	10%	50	393.3	1.6	18.5%	11.0
		20%	50	343.4	1.7	19.3%	11.7

Table 2: Computational results concerning the ALWIBP-1S$_{min}$ model.

$\|W\|$	Var	Inc	Δ	$t(s)$	$m_\uparrow$	$m_\uparrow(\%)$	τ
1	$U[t_i, 2t_i]$	10%	98	13.5	0.2	3.0%	169.4
		20%	96	29.4	0.3	3.2%	160.4
	$U[t_i, 5t_i]$	10%	90	62.0	0.5	5.5%	265.2
		20%	96	32.7	0.4	5.5%	272.8
2	$U[t_i, 2t_i]$	10%	90	65.7	0.5	5.7%	157.8
		20%	93	48.9	0.5	5.8%	152.6
	$U[t_i, 5t_i]$	10%	94	47.9	0.8	9.0%	181.2
		20%	91	79.3	0.8	9.4%	190.6
3	$U[t_i, 2t_i]$	10%	87	86.9	0.7	7.8%	116.6
		20%	89	77.3	0.6	7.7%	129.8
	$U[t_i, 5t_i]$	10%	90	85.6	1.2	14.5%	172.5
		20%	87	101.0	1.3	14.8%	189.8
4	$U[t_i, 2t_i]$	10%	87	108.4	0.9	10.9%	123.3
		20%	81	144.8	0.9	11.1%	123.6
	$U[t_i, 5t_i]$	10%	83	155.2	1.6	18.6%	153.6
		20%	70	214.6	1.7	19.5%	162.2

Table 3: Computational results concerning the ALWIBP-1S$_{50}$ model.

worker in the bottleneck station, through giving him/her a mandatory slack time. The results for these two cases are presented in Tables 2 and 3.

Interestingly, the results show that while maintaining the same rough productivity (in terms of number of work stations) other objectives can indeed be reached. In Table 2 the idle times column present very tiny values whereas in Table 3 a slight increase in the average idle times is shown (due to instances in which the ALWIBP-1 solution presented disabled workers in the bottleneck or with idle times close to zero).

Overall, all versions of the models could be solved in reasonable computation times using the commercial package CPLEX 12.4 (with around 90% of the instances being solved to optimality in the allowed 600s computational time).

5 Conclusions

We propose the Assembly Line Worker Integration and Balancing Problem (ALWIBP), a new assembly line balancing problem arising in lines with conventional and disabled workers. This problem is relevant in a context where companies are urged to integrate disabled workers in their conventional productive schemes in order to cope with legislation issues or to include coorporate social responsibility goals in the production planning process. We develop integer linear models and, through an experimental study on a extensive number of instances, conclude that disabled workers can be not only be included in the assembly lines with little productivity loss but also that other planning goals can be simultaneously considered. Further work on this topic include the proposal of new adjacent objectives, the development of heuristic methods and experimentation on large scale instances.

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