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Job rotation in assembly lines employing disabled workers

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ABSTRACT

In this paper we consider the programming of job rotation in the assembly line worker assignment and balancing problem. The motivation for this study comes from the designing of assembly lines in sheltered work centers for the disabled, where workers have different task execution times. In this context, the well-known training aspects associated with job rotation are particularly desired. We propose a metric along with a mixed integer linear model and a heuristic decomposition method to solve this new job rotation problem. Computational results show the efficacy of the proposed heuristics.

1. Introduction

The World Health Organization (WHO) estimates that 10% of the world population presents some type of deficiency. Among the 610 million disabled people worldwide, it is estimated that 386 million are of working age, but that only a small portion of them execute some form of productive activity. The percentages of unemployment for disabled people differ greatly depending on the country under review. While in the United Kingdom, for example, the unemployment rate for disabled people is 13% (according to the WHO), in many countries this rate is likely to be much higher. In fact, taking the example of Brazil, a research carried out by the Employment Secretary of São Paulo showed that 90% of the disabled population was unemployed in this representative municipality (SERPRO, 2004). These wide divergences only serve to confirm that the non-presence of the disabled in the labor market is often more related to political and social factors rather than to their supposed inability to carry out a productive activity.

In view of the above, different inclusion attempts are being made to further the integration of these citizens in society. Several countries deal with this problem through different integration approaches and the awareness regarding this issue goes beyond the public and governmental spheres. Indeed, under the concept of corporate social responsibility (see, e.g., Kotler and Lee, 2005), an increasing number of companies are becoming concerned with this matter. In this context, the employment of disabled workers is seen as a way of including the interests of society in the company goals.

One of the strategies most commonly adopted in order to facilitate the integration of disable workers into the labor market is the creation of sheltered work centers for the disabled (SWD). These centers serve as a first working place for these workers who will, eventually, be incorporated into the conventional labor market. SWD usually target people who are particularly difficult to integrate. While, on the one hand, these centers receive institutional support and must act as a training center, on the other hand, they must be competitive in the market. The apparent contradiction between these two objectives calls for efficient multi-objective management tools and strategies which are able to conciliate such goals in a single solution.

In this context, we have analyzed the implementation of efficient job rotation strategies in SWD assembly lines.

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Job rotation is well-renowned for increasing employees' abilities (Eriksson and Ortega, 2006) and is therefore used as an *on-the-job* training tool. Our goal is to find rotation schedules that expose the workers to different tasks while respecting some desired productivity levels.

We propose a metric to evaluate the efficiency of job rotation in SWD. This metric maximizes the number of different tasks executed by each worker during a complete rotation period. Along with this metric, we present a mixed integer linear formulation for the problem and a heuristic decomposition procedure for its resolution. We show that the proposed method is able to find good quality solutions within reasonable computation times.

The information included in this paper is organized as follows: the following section presents a brief literature review of the problem. Section 3 details the model presented by Miralles et al. (2007) in the case of production maximization as well as our proposed extension. Section 4 presents the heuristic decomposition method. Then, computational tests on two groups of instances evaluate the efficacy of the proposed approach. Section 6 ends this paper with some conclusions and further research lines.

2. Literature review

In an assembly line there are a number of tasks that must be executed before the final product can be obtained. Needless to say, certain tasks can only be executed once others have been completed, thus establishing a series of precedence constraints. The tasks are executed in workstations which are traditionally organized in a sequential manner. The fundamental optimization problem, in this case, is the attribution of tasks to the workstations. The described case is known as the single assembly line balancing problem (SALBP). When the number of stations is minimized, the problem is referred to as SALBP-1. When the objective is to minimize the cycle time, the problem is labeled as SALPB-2. A classic review of exact methods to solve this problem was presented by Baybars (1986). More recently, exact and heuristic methods for SALPB have been catalogued by Scholl and Becker (2006) while Boysen et al. (2007, 2008) have presented classifications of assembly line balancing problems.

In the SALBP, each employee is equally efficient in the execution of each task and, for this reason, the SALBP does not adequately address the problem of determining the assembly lines at SWD. In this case, workers have different efficiencies, which depend on the executed task. Different worker performances in assembly lines have been studied by Mansoor (1968). In that paper, the author considered different levels of performance between workers and proposes a heuristic solution. Bartholdi and Eisensteein (1996) analyzed the case in which workers have different work speeds in a particular assembly line, the Toyota Swen System. In ordinary assembly lines, Gel et al. (2002) and Hopp et al. (2004) studied the case where there are two types of workers: fast and slow workers. On the same line, Corominas et al. (2008) have recently proposed a binary linear program for a problem with skilled and unskilled workers.

Other studies that take into account variable task processing speeds are those dealing with the installation of machines. Different machines are capable of executing different tasks at different speeds. Combining the decision of which equipment to select with the network balancing problem gives rise to the assembly line design problem (ALDP). A survey of optimization methods for the ALDP was completed by Rekiek et al. (2002). Although it deals with different task execution times, the ALDP is different to the problem faced at the SWD. To start with, at SWD the aim is not to minimize the cost of machines that need to be installed, but rather to employ as many workers as possible. More importantly, in the case of the SWD, each worker is unique and may only be placed once, contrary to what occurs in the ALDP, when multiple similar equipment units may be acquired.

To our knowledge, the problem faced by the SWD has been only addressed very recently in the literature. Miralles et al. (2007, 2008) have introduced the problem of assigning workers in SWD and named it the assembly line worker assignment and balancing problem (ALWABP). In those papers, the authors have considered different execution times per pair (worker $\times$ task) and not only different performance levels among workers. Similarly to what occurs in the SALBP, when we wish to minimize the number of stations, the problem is called ALWABP-1 and when the objective is to minimize the cycle time, the problem is called ALWABP-2, the latter situation being the most common at SWD. For this reason, in Miralles et al. (2007), the authors have presented a mathematical model for the ALWABP-2 and a case study based on a Spanish SWD. Miralles et al. (2005) have extended the ALWABP model used in the latter two papers to deal with the case where the assembly lines are U-shaped. In all these articles, the authors have considered the job rotation problem an interesting and practical topic for further research, motivating the work presented here.

Programming job rotation is a rather complex task even in the simpler SALBP case, in which workers have similar operating times. It can be hard to obtain solutions even for moderately sized problems (Carnahan et al., 2000) and even when addressing only the assignment problem (Butkovič and Lewis, 2007). For this reason, different heuristic techniques have been proposed in the literature to obtain good solutions. Carnahan et al. (2000) dealt with the job rotation problem to minimize the number of extenuating tasks being undertaken by the same worker. Solutions were obtained with integer linear programming (for problems with up to 128 decision variables) and with genetic algorithms. Other techniques employed include simulated annealing (Seçkiner and Kurt, 2007), optimization algorithms based on ant colonies (Seç kiner and Kurt, 2008) and greedy algorithms with diversification (Tharmmaphornphilas and Norman, 2007).

In the case of ALWABP, the difficulty of programming job rotation schedules is increased. Since we have heterogeneous task processing times, a simple exchange of two tasks can produce a serious imbalance in the line, causing an increase in the cycle time. For this reason, one of the goals of this paper is to develop new metrics and strategies that allow us to cope simultaneously with these two conflicting goals: job rotation and production efficiency.

Other multi-objective problems have already been described in the assembly line balancing problem literature. Malakooti (1991, 1994) and Malakooti and Kumar (1996) considered a multi-objective assembly line balancing problem with capacity and cost-oriented objectives and propose different solution approaches including generation of efficient alternatives, interactive approaches and goal programming. Gökçen and Erel (1997) solved a mixed-model ALBP also with the aid of goal programming. McMullen and Frazier (1998) proposed a simulated annealing algorithm to solve an ALBP in which two main goals were considered: total cost (labor and equipment) per part, and the degree to which the desired cycle time was achieved. Vilarinho and Simaria (2002) proposed a two-stage heuristic to deal with a mixed-model ALBP with parallel workstations, with the goals of minimizing the number of workstations along the line, for a given cycle time, and balancing the workloads between and within workstations. Gökçen and Ağpak (2006) applied multi-criteria goal programming to the case of U-shaped lines while McMullen and Tarasewich (2006) used an ant colony optimization algorithm to solve a Generalized ALBP with multiple goals such as the system utilization, the probability of jobs being completed within a certain time frame and system design costs. More recently, Özcan and Toklu (2009) have proposed multi-criteria goal-programming and fuzzy goal-programming models for a two-sided assembly line balancing problem in which single criteria approaches might lead to unrealistic solutions.

The case faced in this paper differs from other multi-objective problems described in the literature in the fact that the metric developed is associated with a job rotation context. We propose maximizing the number of different tasks executed by each worker while maintaining the productivity at reasonable levels. The idea is to obtain an adequate trade-off between the two main goals of an SWD, the training of disabled workers and the production efficiency. This strategy fits nicely in the concept of corporate social responsibility. Indeed, Porter and Kramer (2002, 2006) propose that between pure philanthropy and pure business could lay a convergence point, where both social and economic terms coincide positively. This multi-criteria social/economical point of view (see, e.g., Schneeweiss, 2000; Koch, 2000; Brans, 2002; Gallo, 2004; Wenstop and Myrmel, 2006; Katayama and Hwang, 2008) motivates the developments presented in this article.

3. Mathematical models

In this section, we present a mixed integer linear formulation for the job rotation problem in SWD. The proposed formulation is an extension of the model proposed by Miralles et al. (2007) for the ALWABP. The notation used and the original model are reproduced as follows:

Notation:

i,j	indexes for tasks
w	index for workers
s	index for workstations
N	set of tasks
W	set of workers
S	set of workstations
C	cycle time
p_{wi}	processing time for task i when executed by worker w
D_j	set of tasks that immediately precede task j in the precedence graph
x_{swi}	binary variable; equal to 1 only if task i is assigned to worker w at workstation s
y_{sw}	binary variable; equal to 1 only if worker w is assigned to workstation s
M	constant such that $M \geq \|N\|$

The model can thus be written as

$$\text{Min}\, C \tag{1}$$

s.t.

$$\sum_{w \in W} \sum_{s \in S} x_{swi} = 1 \quad \forall i \in N, \tag{2}$$

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

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

$$\sum_{w \in W} \sum_{s \in S} s x_{swi} \leq \sum_{w \in W} \sum_{s \in S} s x_{swj} \quad \forall i,j \in N | i \in D_j, \tag{5}$$

$$\sum_{i \in N} p_{wi} x_{swi} \leq C \quad \forall w \in W, \ \forall s \in S, \tag{6}$$

$$\sum_{i \in N} x_{swi} \leq M y_{sw} \quad \forall w \in W, \ \forall s \in S, \tag{7}$$

$$y_{sw} \in \{0,1\} \quad \forall s \in S, \ \forall w \in W, \tag{8}$$

$$x_{swi} \in \{0,1\} \quad \forall s \in S, \ \forall w \in W, \ \forall i \in N. \tag{9}$$

Model (1)–(9) aims at minimizing the cycle time while respecting the problem characteristics. Constraints (2) guarantee that each task is executed by a single worker, at a single workstation. Constraints (3) and (4) imply that each worker is assigned to a single workstation and that each workstation receives a single worker. Precedence relations between tasks are respected due to constraints (5), while constraints (6) and (7) allow each worker to execute more than one task, as long as the cycle time is respected.

The model presented above considers a single allocation of workers and tasks to machines. In other words, at every shift, each worker will execute the same tasks in the same machine. Job rotation increases the exposure of workers to tasks, by defining a rotation period. This rotation period is divided in a number of subperiods and, at each subperiod, new assignments are made, changing the tasks assigned to each machine and, in the case of the ALWABP, possibly also changing the assignment of workers to machines. In this way, at the end of one rotation period, each worker has dealt with a higher number of tasks while spending less time with each individual task.

In order to extend formulation (1)–(9) to the job rotation case, a new objective function must be defined. Since one of the functions of an SWD is to prepare workers to access the conventional labor market, we considered the objective of maximizing the number of diverse tasks executed by each worker, during a complete rotation period. The idea is that confronting a worker with a maximum number of different tasks will challenge his/her skills and serve as a form of training. The former objective function appears as a new constraint that imposes an upper bound on the cycle times, in order to maintain a certain efficiency level.

The job rotation model is thus obtained through the repetition of constraints (2)–(9) for each subperiod. This is achieved by adding an index associated with the current subperiod to variables x_{swi} and y_{wi}, in addition to the inclusion of coupling constraints. New binary variables z_{wi} are used. Variable z_{wi} equals 1 if worker w executes task i in at least one of the subperiods that form the complete rotation period. With the aid of the following additional notation:

t	index for rotation subperiods
T	number of subperiods
C_t	cycle time of subperiod t
$\underline{C}$	maximum mean allowed cycle time
x_{swit}	binary variable; equals 1 only if task i is assigned to worker w at workstation s in subperiod t
y_{swt}	binary variable; equals 1 only if worker w is assigned to workstation s in subperiod t
z_{wi}	binary variable; equals 1 only if worker w executes task i in at least one subperiod

We can write the job rotation model as

$$\text{Max} \quad \sum_{w\in W}\sum_{i\in N} z_{wi} \tag{10}$$

s.t.

$$\sum_{w\in W}\sum_{s\in S} x_{swit} = 1 \quad \forall i\in N, t=1,\ldots,T, \tag{11}$$

$$\sum_{s\in S} y_{swt} \le 1 \quad \forall w\in W, t=1,\ldots,T, \tag{12}$$

$$\sum_{w\in W} y_{swt} \le 1 \quad \forall s\in S, t=1,\ldots,T, \tag{13}$$

$$\sum_{w\in W}\sum_{s\in S} s x_{swit} \le \sum_{w\in W}\sum_{s\in S} s x_{swjt} \quad \forall i,j\in N | i\in D_j,\ \ t=1,\ldots,T, \tag{14}$$

$$\sum_{i\in N} p_{wi} x_{swit} \le C_t \quad \forall w\in W,\ \ \forall s\in S,\ \ t=1,\ldots,T, \tag{15}$$

$$\sum_{i\in N} x_{swit} \le M y_{swt} \quad \forall w\in W,\ \ \forall s\in S,\ \ t=1,\ldots,T, \tag{16}$$

$$\sum_{t=1}^{T} C_t \le T\,\underline{C}, \tag{17}$$

$$z_{wi} \le \sum_{t=1}^{T}\sum_{s\in S} x_{swit} \quad \forall w\in W, i\in N, \tag{18}$$

$$y_{swt}\in\{0,1\} \quad \forall s\in S,\ \ \forall w\in W,\ \ t=1,\ldots,T, \tag{19}$$

$$x_{swit}\in\{0,1\} \quad \forall s\in S,\ \ \forall w\in W,\ \ \forall i\in N,\ \ t=1,\ldots,T. \tag{20}$$

The new objective function (10) maximizes the number of different tasks executed by each worker. Constraints (11)–(16) guarantee that the original problem constraints are respected at each subperiod. Coupling constraints (17) and (18) guarantee that the mean cycle time of the final solution does not exceed the desired value ($\underline{C}$), and that z_{wi} variables do indeed represent the execution (or not) of task i by worker w, respectively.

4. Decomposition method

When compared to the original model, (1)–(9), the new formulation presents a significantly higher number of constraints and variables. As outlined in the section that follows, the new model resolution becomes impractical even for small values of T. Therefore, to solve the new problem, a heuristic method must be used.

In this section, we propose a method that is based on the original model. The basic idea is to sequentially solve problems in the form (1)–(9), but taking into account the desired objective: the maximization of the, different tasks executed by each worker. This can be achieved in two stages: first, we solve the original problem and we assign the obtained solution to the first rotation subperiod. Then, for each subsequent subperiod, we solve problems of the form (1)–(9) with two modifications: (1) the objective function is modified so that it contains only the x_{swit} variables associated with (w,i) pairs which have not been part of a previous solution and (2) a constraint on the maximum cycle time is added. Algorithm 1 details the procedure.

Algorithm 1. Decomposition method.

Solve the original problem (1)–(9): Let $\widetilde{x}_{swi1}$ be the optimal solution and $\widetilde{C_1}$ its objective value.
Let $\overline{C} = \widetilde{C_1}$
Let $\overline{z}_{wi} = \sum_{s\in S}\widetilde{x}_{swi1}$
for t $= 2\ldots T$ **do**
  New objective function $= \sum_{s\in S}\sum_{w\in W, i\in N|\overline{z}_{wi}=0} x_{swi}$
  New decomposition constraint: $C \le (T\,\underline{C} - \overline{C})/(T-t+1)$
  Solve the modified problem. Let $\widetilde{x}_{swit}$ be the optimal solution of variables x_{swi}, and $\widetilde{C}_t$ the associated cycle time.
  $\overline{z}_{wi} = \max(\overline{z}_{wi}, \sum_{s\in S}\widetilde{x}_{swit})$
  $\overline{C} = \overline{C} + \widetilde{C}_t$
end for
Output: $\widetilde{x}_{swit}$

The basic idea behind Algorithm 1 is to successively run optimizations, one per period, maximizing the number of different tasks executed by each worker at each stage. The first optimization minimizes the cycle time (line 1). The $\overline{C}$ accumulator stores the sum of the previous subperiods cycle times, while variables $\overline{z}_{wi}$ indicate if task i has already been executed by worker w. The values for these variables are initially set at lines 2 and 3 and updated at lines 8 and 9. At each iteration a new target function contemplates only the x_{swi} variables for which worker w has not yet executed task i, i.e., those for which $z_{wi} = 0$ (line 5). Also, at each iteration the cycle time limit is modified: the idea is to allow the remaining subperiods to have cycle times that will yield a total mean cycle time of $\underline{C}$ (line 6). Note that an alternative would have been to bound the cycle time at each period by $\underline{C}$. The idea behind the computations in line 6, however, is to allow the latter subperiods to make use of an eventual "time-capacity" not used by the early subperiods. The result of the optimization carried out at each iteration t is kept in variables $\widetilde{x}_{swit}$ (line 7). The complete set of these variables is returned as the algorithm solution (line Output).

The strategy used by Algorithm 1 can be classified as greedy since, once a decision is made, it remains unchanged during the whole optimization process. The interesting aspect of applying such strategy to problem (10)–(20) is the fact that the algorithm is able to correct or partially correct a possibly *wrong* decision made in earlier stages. Indeed, the independency between the assignments in each of the subperiods allows the proposed modified objective function to guide the algorithm towards good global solutions. In the next section, a series of computational results confirm the efficacy of the method.

5. Computational study

In this section, we describe the computational experiments carried out in order to test the efficiency of the proposed solution method. Section 5.1 describes the benchmark instances and methodology used while Section 5.2 present the numerical results.

5.1. Benchmark and methodology

Both models (10)–(20) and the decomposition method proposed in the previous section have been implemented and tested with a group of instances selected from the ALWABP benchmark taken from Chaves et al. (2007). These instances were originally generated from the well-known classical SALBP collection by Hoffmann (1990). From this benchmark, we used two families of instances: the Heskia family, with 28 tasks and containing groups of problems with 4 and 7 workers; and the Roszieg family, with 25 tasks and containing groups of problems with 4 and 6 workers. As described in Chaves et al. (2007), every group contains problems with high or low values for parameter *inc* (10% or 20% task-worker incompatibilities randomly defined a priori in the tasks-workers matrix), and high or low values for parameter *var* (variability of task execution times for the different workers, following the distributions $U[1, t_i]$ and $U[1, 3t_i]$ for low and high variability, respectively, where t_i is the original task time of the corresponding SALBP Hoffman's instance). By choosing the Heskia and Roszieg families, we also have a representative sample of instances regarding the topology and density of the precedence network, since the Heskia network has a low order strength (indicator that measures the structural properties of the precedence network) of 22.59, while the Roszieg network has a high order strength of 71.67.

In brief, each family contains 80 examples, divided into eight groups that differ in terms of the number of workers, n, the variability of the task execution times according to the workers, *var*, and the level of (worker $\times$ task) incompatibilities, *inc*. The details of the groups of instances are presented in Table 1.

For each instance, we consider the cases where the cycle times can be increased by 5%, 10%, 25% or 50% due to job rotation. This implies a reduction in productivity since we allow larger cycle times, when compared to the cycle time obtained without job rotation. The parameter R indicates the allowed cycle time. We use $R = 1.05, 1.1, 1.25$ and 1.5. To exemplify, $R = 1.05$ indicates that the average cycle time (when all the subperiods are considered) is at most $\underline{C} = 1.05\widetilde{C_1}$, where $\widetilde{C_1}$ is given by the solution of the single-period problem (1)–(9). Concerning the number of subperiods, we analyzed the case $T = |W|$. In order to compare the heuristic method to the optimum solution for model (10)–(20), we also considered the case $T = 2$, for the instances with four workers. The mixed integer linear programs were solved using CPLEX 11.0, on a machine operating under the Linux operating system, with a 2.33 GHz processor and 4 GB of RAM memory.

5.2. Results

The first tests carried out compared the results of the decomposition Algorithm 1 to the exact solution of the multi-period model (10)–(20). The results are compiled in Tables 2 and 3.

The results presented in Tables 2 and 3 suggest that the heuristic solutions are of good quality, presenting average gaps of less than 2.00%. The proposed method uses a small fraction of the time needed by CPLEX to solve problem (10)–(20): 7.27s against 3080.67s (in average, for the Heskia examples) and 4.36s against 310.77s (in average,

Table 1
Characteristics of instances by group.

Group	Nb instances	*var*	*inc*	Nb Workers		Nb Tasks	
				Heskia	Roszieg	Heskia	Roszieg
1	10	Low	Low	4	4	28	25
2	10	Low	High	4	4	28	25
3	10	High	Low	4	4	28	25
4	10	High	High	4	4	28	25
5	10	Low	Low	7	6	28	25
6	10	Low	High	7	6	28	25
7	10	High	Low	7	6	28	25
8	10	High	High	7	6	28	25

Table 2
Results for $T = 2$ – Heskia, groups 1–4.

R	Group	Optima		Heuristic	
		Value	$t(s)$	Value (gap)	$t(s)$
1.05	1	48.80	4962.66	47.60 (2.46%)	8.85
	2	47.90	959.62	47.00 (1.88%)	4.42
	3	48.80	7458.58	47.10 (3.48%)	9.57
	4	49.00	12 985.08	47.90 (2.24%)	10.10
1.1	1	51.80	4080.58	50.40 (2.70%)	9.44
	2	51.90	905.09	51.00 (1.73%)	3.93
	3	52.90	6447.97	51.10 (3.40%)	10.04
	4	52.00	13 438.47	50.40 (3.08%)	11.05
1.25	1	55.30	2791.82	54.40 (1.63%)	9.29
	2	55.30	262.72	54.50 (1.45%)	3.73
	3	55.50	3190.82	55.10 (0.72%)	8.30
	4	55.80	3570.28	54.80 (1.79%)	8.07
1.5	1	55.90	119.56	55.90 (0.00%)	5.02
	2	55.90	23.09	55.70 (0.36%)	2.96
	3	56.00	29.65	56.00 (0.00%)	4.95
	4	56.00	78.51	55.90 (0.18%)	6.56
Mean		**53.05**	**3831.53**	**52.18** (**1.65%**)	**7.27**

Table 3
Results for $T = 2$ – Roszieg, groups 1–4.

R	Group	Optima		Heuristic	
		Value	$t(s)$	Value (gap)	$t(s)$
1.05	1	43.20	430.91	42.40 (1.85%)	5.06
	2	37.50	60.34	36.80 (1.87%)	2.78
	3	43.80	1397.96	42.80 (2.28%)	7.19
	4	42.60	938.49	42.00 (1.41%)	5.38
1.1	1	46.00	253.54	44.80 (2.61%)	5.11
	2	39.80	26.79	39.20 (1.51%)	2.68
	3	48.50	941.58	46.70 (3.71%)	6.54
	4	47.60	449.73	46.60 (2.10%)	4.60
1.25	1	49.50	128.33	48.20 (2.63%)	4.36
	2	44.30	22.95	43.00 (2.93%)	2.70
	3	49.90	137.02	49.30 (1.20%)	4.74
	4	49.40	71.94	49.30 (0.20%)	4.06
1.5	1	50.00	29.08	49.60 (0.80%)	4.03
	2	47.40	33.05	46.10 (2.74%)	2.42
	3	50.00	16.28	50.00 (0.00%)	4.39
	4	49.90	34.36	49.50 (0.80%)	3.75
Mean		**46.21**	**310.77**	**45.39** (**1.77%**)	**4.36**

for the Roszieg examples). The fact that the Roszieg examples are more easily handled by the multi-period formulation is, probably, connected to the fact that they have a higher number of precedence constraints, which facilitates convergence in the branch-and-cut method used.

For a number of subperiods higher than two, we compared the values obtained by the heuristic method with the theoretical maximum value of different tasks carried out by the workers. We considered a number of subperiods equal to the number of workers in each example. In this way, the theoretical limit of different tasks in a complete period is given by $T|N| - I$, where T is the number of subperiods considered, $|N|$ is the number of tasks and I is the number worker $\times$ task incompatibilities. In other words, the upper limit is given by the situation in which each task is carried out by a different worker at each subperiod (discounting the incompatibilities). This bound is presented in Tables 4 and 5 in the column labeled "Upper bound". The tables also show the values obtained by the heuristic for different values of the parameter used to restrict the cycle time, R.

The values in Tables 4 and 5 confirm the expected results: as the bounds on the cycle times become less restrictive, more differing tasks are executed by each worker. By varying the parameter R, a Pareto-curve of solutions can be obtained and the manager can choose the acceptable loss in productivity. In demand-varying environments, this choice might be guided by the market: high demand periods would ask for solutions obtained for low values of R and, therefore, with high productivity profiles. Analogously, managers could use periods with lower demands as the time to encourage the personal development of workers, using the solutions obtained for high values of R. Note that this analysis can be extended to assembly lines outside SWD. In these cases, lower values for parameter R are likely to be chosen. The results show that even for low values of the parameter R, job rotation leads to a significant number of new tasks different from those already carried out by the workers in the optimal solution of (1)–(9).

Concerning the proposed upper bound, note that it is weak for the cases where a high performance (low value of R) is required. This happens because the upper bound calculation is solely based on the number of *a priori* incompatibilities (worker $\times$ task). In cases where a low value of R is needed, many other pairs (worker $\times$ task) end up being forbidden due to performance reasons. This fact can be confirmed by comparing the upper bounds to the optimal values obtained for the case $T = 2$ (Tables 2 and 3). In those cases, we cannot use the same upper bound as defined before, since it is based on the assumption that the number of periods and workers are the same. However, a similar measure can be obtained simply by solving the model for a very large value of R. If this is done, we obtain the values presented in Table 6. As expected, we can observe that the upper bound becomes a better approximation for the optimal solutions as the values of R increase, presenting interesting approximations already for the cases $R = 1.25$ and 1.5.

In what concerns computational burden, it should be noted that the heuristic method computational times (columns $t(s)$ in the tables) are low even for situations with a higher number of workers on the line (6 or 7). However, since this method relies on the resolution of mixed integer linear problems, as the size of instances grows, its efficiency might be compromised. This problem could be dealt with by eventually changing the exact resolution of the obtained ALWABP problems for heuristic ones.

Table 4
Heuristic results for Heskia instances.

Group	No. worker	T	Upper bound	$R=1.05$		$R=1.1$		$R=1.25$		$R=1.5$	
				Sol	$t(s)$	Sol	$t(s)$	Sol	$t(s)$	Sol	$t(s)$
1	4	4	102.60	65.30	14.74	74.60	18.32	86.00	18.35	93.50	12.08
2	4	4	93.20	61.70	8.39	69.60	9.05	81.40	8.99	85.80	7.06
3	4	4	101.90	64.60	18.21	73.80	20.79	87.00	20.67	95.90	12.54
4	4	4	101.30	65.80	19.29	74.10	19.88	87.30	20.56	95.30	11.78
5	7	7	174.50	87.20	253.50	99.60	336.02	122.70	590.63	141.40	829.04
6	7	7	164.00	103.40	442.70	112.00	681.55	123.70	788.20	135.80	666.90
7	7	7	175.90	110.20	320.45	120.60	441.87	136.70	778.11	149.90	902.23
8	7	7	175.40	96.90	380.18	112.20	592.42	130.00	890.82	147.50	1329.80

Table 5
Heuristic results for Roszieg instances.

Group	No. worker	T	Upper bound	$R=1.05$		$R=1.1$		$R=1.25$		$R=1.5$	
				Sol	$t(s)$	Sol	$t(s)$	Sol	$t(s)$	Sol	$t(s)$
1	4	4	89.50	55.40	8.04	61.10	8.34	73.70	8.21	79.00	7.25
2	4	4	82.40	44.70	4.20	48.60	4.33	61.70	4.23	68.00	4.25
3	4	4	92.50	58.20	11.48	68.60	11.43	78.80	9.41	86.00	6.72
4	4	4	89.70	57.40	9.50	67.80	8.89	78.60	7.11	81.50	6.16
5	6	6	134.60	79.90	373.58	90.40	422.95	113.40	418.52	126.30	300.37
6	6	6	128.50	67.60	170.43	80.50	182.19	99.30	186.59	111.30	171.02
7	6	6	135.30	79.10	307.12	92.50	425.65	115.80	440.15	129.50	277.54
8	6	6	136.60	73.00	304.76	89.20	380.92	114.30	495.66	129.00	285.56

Table 6
Upper bounds and optimal solutions for instances of groups 1–4, $T=2$.

Family	Group	UB ($R=10$)	$R=1.05$	$R=1.1$	$R=1.25$	$R=1.5$
Heskia	1	55.90	48.80	51.80	55.30	55.90
	2	55.90	47.90	51.90	55.30	55.90
	3	56.00	48.80	52.90	55.50	56.00
	4	56.00	49.00	52.00	55.80	56.00
Roszieg	1	50.00	43.20	46.00	49.50	50.00
	2	48.50	37.50	39.80	44.30	47.40
	3	50.00	43.80	48.50	49.90	50.00
	4	50.00	42.60	47.60	49.40	49.90

The results suggest that it is possible to find a trade-off between profit maximization and the SWD social goals. Indeed, the algorithm was able to find solutions in which not so much productivity was lost when increasing the workers welfare through job rotation approaches. Furthermore, one can argue that this loss of productivity could eventually be recovered in the long term as a result of a good work environment with high worker motivation and of the workers increased qualification.

6. Conclusions

In this paper, we analyzed the programming of job rotation in the assembly line worker assignment and balancing problem. This problem arises in production lines of sheltered work centres for the disabled, where the execution time for each task differs from worker to worker. Due to its high heterogeneity, job rotation in this type of lines becomes a complex scenario. The main difficulty is that a simple exchange of tasks between workers might imply a high imbalance on the line resulting in a loss in efficiency. This problem had not yet been addressed in the literature. We proposed a metric for the problem, as well as a mixed integer linear model and a heuristic decomposition resolution method. The developed approach proved to be efficient, both in terms of solution quality and computational effort.

The obtained results suggest that even in very complex contexts such as those found in SWD, it is possible to improve the welfare of workers by applying job rotation, without important losses in productivity. We consider this as the most important conclusion, which fits with the corporate social responsibility concept. Indeed, in such framework, giving solutions to business problems no longer implies just profit maximization but should also consider finding the best trade-off that globally satisfies the distinctive affected stakeholders. As part of future research, we intend to explore new scenarios where this global philosophy can be applied. From a more technical point of view, further research should include the development of methods that do not rely upon the solution of mixed integer linear problems and real case testing.

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