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Assembly line balancing with inexperienced and trainer workers

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Abstract. In this paper, we present a simple assembly line balancing problem for two different sets of workers: trainer workers who are more experienced and likely older, and inexperienced workers who are usually younger and require more time to perform some tasks. Therefore, the main characteristic of this problem is that trainer workers are involved in helping and supporting inexperienced ones in executing some tasks which are more complicated to be carried out. Moreover, task times vary according to the stations where they can be performed due to different sets of equipment we can find in each of them. The problem is modelled as a linear program and solved optimally by applying it to a real-case application. The developed model can be successfully applied in order to help companies to manage a high level of turnover.

Keywords: Assembly Line Balancing, Inexperienced workers, Training activities, Employee turnover, Production system

1 Introduction

Fierce global competition forces manufacturing companies to strive for their operational efficiency. One of the key factors on the agenda of production managers, who constantly requires optimization, is the planning and use of resources. An enormous scientific effort is dedicated to developing intelligent and reliable algorithms that are based on the analysis of the data produced and recorded in the context of Industry 4.0 [1]. However, the implementation of such an approach in human-centred manufacturing environments, where human resources are highly involved in the manufacturing process, is not straightforward. For evident reasons, in practice, human factors cannot be ignored when it comes to planning manufacturing activities involving human operators. Since, in manufacturing, a high number of tasks are still human-centred and their performances largely depend more on workers than on machines [2]. This happens especially in big size highly customized product assembly systems [3]. The workforce may vary in terms of many factors, such as skill, age, gender and physical attributes and these differences can affect the overall performances of the production system in terms of time i.e. [4], cost i.e. [5], and throughput i.e. [6]. Moreover, some companies face a high turnover employee problem. Therefore, the consideration of workers'

differences and characteristics in production systems plays an important role, particularly in all human-centered fields like manual assembly systems [7]. In this study, we propose a linear programming model with aim of cost minimization, which allows to balance the assembly line by taking into account different workers in terms of experience. Workers can be experienced or inexperienced due to their years of working or age. This factor can impact the task processing time directly. Therefore, in this study, experienced workers can be assigned to stations, to assist or train inexperienced workers. Furthermore, the number of experienced workers has been considered limited in this paper and they mainly play a trainer's role to supervise and help inexperienced workers to perform tasks within a given cycle time due to this help. On the other hand, inexperienced workers may perform tasks (depending on the types of tasks) in higher time and for this reason, an increment time coefficient is taken into account. Moreover, the task time is not only depending on the workers, in this study but also it depends on the equipment of the station, meaning that each task may have a different duration according to the station where it is assigned.

Besides, as the experienced workers may perform tasks faster, they also may suffer from some functional incapacities simultaneously. For example, age can have a positive impact on workers' experience, while it can decline functional capacities. Therefore, ageing workers could use their skills to compensate for capacity reduction [8]. Hence, in this study, we aim to use and manage the current workers in an assembly line in a way to simply reduce the total cost but to consider workers' differences and the integration of experienced and inexperienced workers in the assembly line. In this way, consequently, inexperienced workers can be helped to promote themselves to be more trained and well-prepared for the future under the supervision of skilled workers. On the other hand, an appropriate condition can be guaranteed for experienced workers (e.g. ageing workers) to reduce their physical workload and prevent them from early retirement as also pointed as an issue by previous studies [9]. Therefore, this issue is timely due to the higher turnover in the workforce particularly considering Covid-19 emergency over the last year.

The remainder of this paper is organized as follows. Section 2 provides a literature review of studies related to assembly line balancing problem considering workers' skill and experience. Section 3 presents the problem description and model formulation. Section 4 describes the model application to a real case study and discusses the obtained results. Finally, Section 5 presents conclusions and future perspectives.

2 Literature review

Workers can vary between each other in terms of, for example, skill level, age, gender and physical capability. Therefore, not every worker can perform every task at the same processing time since human characteristics may differ [9]. These differences can be influential widely in sections with a high percentage of workers' involvement, like an assembly line in production systems. Initially, the Simple Assembly Line Balancing Problem (SALBP) has been widely discussed in the literature by considering equal workers in terms of experience, age and wage i.e. [10]. Then, several studies and models

have been proposed by including ergonomics, postures, physical fatigue during the assembly line design phase [11].

As the installation of an assembly line requires large investments, assembly line balancing problems can be distinguished based on objectives addressed through such as cost- or profit-oriented models. A particular stream of the cost-oriented models involves selecting and assigning workers with different skill levels to the tasks and stations. For example, [12] developed a model for balancing assembly line with the inclusion of both skilled workers (permanent) and unskilled workers (temporary) with a goal of minimization of temporary workers and consequently the total cost. In their studies, the unskilled workers are temporary workers who are applied to help skilled workers, when it is needed to increase production volume during some months due to the seasonal nature of the demand for its product. Moreover, [13] considered the balancing of an assembly line with consideration of both skilled and unskilled workers (in this case unskilled workers were not temporary) to minimize the total annual workstation costs and annual salaries of skilled and unskilled workers. They assumed that unskilled workers could be assigned to help skilled ones to reduce task processing time. Besides, concerning this issue, other studies have put attention on the mixed-model assembly line balancing with the inclusion of unskilled temporary workers to minimize the summation of workstation and workers' cost [14,15]. It should be noted that studies that considered workers' differences in terms of disability also exist. Since the pioneering study in [16], the integration of workers with disabilities in assembly line balancing and worker assignment has received considerable attention among researchers [17].

In this study, our main aim is to balance a simple assembly line by taking into account both experienced and inexperienced workers in the assembly line. We consider the case where the number of experienced workers is limited, and inexperienced workers need to be assisted and trained by trainers and skilled workers. Furthermore, in this study all workers are permanent, and they are assigned to stations according to their skills. We assume that inexperienced workers can do some tasks in a standard task time, while they are not able to do other tasks in a standard time due to the task's skills demand. In this case, inexperienced workers can be helped and trained by experienced ones according to their availability.

3 Mathematical Formulation

Our model aims to balance a single assembly line by taking into consideration the inexperienced workers and trainer workers. In companies characterized by a high turnover level, workers involved in the assembly process might not have the appropriate experience to be able to execute all types of tasks. However, to face this problem training activities can be performed by some highly skilled workers that have been worked in the company for several years. In this case, they know all tasks as well as the product to assemble. In such a scenario, if trainers are involved, two benefits can be achieved: first, the cycle time can be reduced, then, inexperienced assemblers can improve their competencies. Therefore, here, a mathematical model is developed to integrate the two

sets of workers with consideration of different corresponding costs and task times. The following assumptions are considered:

- 1) There are two sets of workers: assemblers and trainers.
- 2) Assemblers have a different level of experience; they can perform all tasks or just some of them.
- 3) Trainers are highly skilled, and they are involved in the assembly line to supervise or train inexperienced workers.
- 4) The number of trainers in the line is limited and they have higher salary cost.
- 5) In each workstation, either only one assembler is assigned to a workstation or a tandem of a trainer and one assembler.
- 6) The task time varies according to the station where it is performed and the workers performing it.
- 7) If a trainer is involved in a workstation the time required to perform some tasks can be reduced.
- 8) We have a maximum number of workstations and we can decide to open just some of them according to their operating cost.
- 9) The cycle time is known.
- 10) Precedence relations among tasks must be respected.

Table 1. List of all indexes, parameters, variables and decision variables.

Indexes	
i, k	Index for tasks
j	Index for workstation
w	Index for workers
t	Index for trainers
Parameters	
I	Number of tasks
J	Number of workstations
W	Number of workers
T	Number of trainers
CW	Cost of workers
CT	Cost of trainers
C_j	Cost of workstation
Ct	Cycle time
A	Set of all precedence among tasks
t_{ijw}	Processing time for task i in workstation j by worker w (it can assume a value ≥ 1 and ∞ if worker w cannot perform the task)
\hat{t}_{ijt}	Reduction time for task i if a trainer t is involved in workstation j (it assumes a value $< t_{ijw}$ and it is 0 if no reduction can be achieved)
Variables	
Cost	The total costs of the assembly system
ST_j	The time of workstation j
Decision variables	
v_j	Boolean variable that assumes a value 1 if workstation j is opened, 0 otherwise
x_{ijw}	Boolean variable that assumes a value 1 if task i is assigned to workstation j to worker w , 0 otherwise

x'_{ijt}	Boolean variable that assumes a value 1 if trainer t is involved in workstation j for task i , 0 otherwise
z_{jw}	Boolean variable that assumes a value 1 if worker w is assigned to workstation j , 0 otherwise
z'_{jt}	Boolean variable that assumes a value 1 if trainer t is assigned to workstation j , 0 otherwise

According to Table 1 and the assumptions previously made our model is defined as follows:

$$\text{O.F.} \quad \text{Minimize Cost} \quad (1)$$

Subject to

$$\sum_j \sum_w x_{ijw} = 1, \forall i = 1, \dots, I \quad (2)$$

$$x_{ijw} \leq z_{jw}, \forall i = 1, \dots, I; \forall j = 1, \dots, J, \forall w = 1, \dots, W \quad (3)$$

$$x'_{ijt} \leq z'_{jt}, \forall i = 1, \dots, I; \forall j = 1, \dots, J, \forall t = 1, \dots, T \quad (4)$$

$$\sum_w z_{jw} \leq v_j, \forall j = 1, \dots, J \quad (5)$$

$$\sum_j \sum_w j x_{ijw} \leq \sum_j \sum_w j x_{kjw}, \forall (i, k) \in A \quad (6)$$

$$\sum_i \sum_w t_{ijw} x_{ijw} - \sum_i \sum_t t_{ijt} x'_{ijt} \leq C t v_j, \forall j = 1, \dots, J \quad (7)$$

$$\sum_j z_{jw} \leq 1, \forall w = 1, \dots, W \quad (8)$$

$$\sum_w z_{jw} \leq 1, \forall j = 1, \dots, J \quad (9)$$

$$\sum_j z'_{jt} \leq 1, \forall w = 1, \dots, W \quad (10)$$

$$\sum_t z'_{jt} \leq 1, \forall j = 1, \dots, J \quad (11)$$

$$x_{ijw}, x'_{ijt}, z_{jw}, z'_{jt}, v_j \in \{0; 1\} \quad (12)$$

$$Cost \in \mathbb{R} \quad (13)$$

Where:

$$Cost = \sum_j [\sum_t C T z'_{jt} + \sum_w C W z_{jw} + C_j y_j]$$

The objective function defined in (1) minimizes the cost of the whole assembly line by including the trainer and assembler workers costs and the operating costs of opened workstations. Constraint (2) guarantees that each task is assigned to exactly one station and one assembler. Constraints (3) and (4) guarantee that a task i can be assigned to an assembler (3) or a trainer (4) at workstation j if this assembler or this trainer is assigned to the same workstation. Constraint (5) verifies that if station j is open there is at most one assembler assigned to it. Constraint (6) ensures the respect of precedence relations among tasks. Constraint (7) guarantees the respect of cycle time. Constraint (8) and (9) ensure that a worker can be assigned only to one workstation and, in each workstation, we can have at most an assembler worker. The same is defined with constraints (10) and (11) for trainer workers. Finally, constraints (12) and (13) are domain constraints for the decision variables.

4 Numerical case and discussion

We test our model by considering a real assembly system in which 71 tasks are performed to obtain the final product. The model is solved with Cplex V12.9.0 with default parameters. The computational experiments were conducted with Intel(R)Core™ i7-6700HQ 2.60Ghz and 16GB RAM. The precedence constraints are shown in Figure 1.

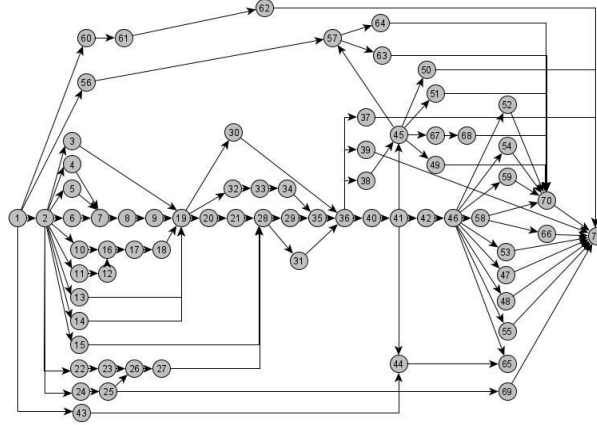


Fig. 1. Precedence constraints

Six problem instances have been solved, each one having a different cycle time. In all cases, we assume to have 2 trainer workers, 5 assemblers with different experience level: one worker having experienced just for some tasks, two unskilled with no experience, two having experience and requiring help just for some tasks.

As costs we consider the ratio between the salary of the trainer and the assembler and we assume it equal to 1.3. Then, we consider the ratio between the operating cost of a workstation and an assembler and we assume it equals to 3. We consider five values of cycle time: 35, 40, 45, 50, 55 and 60 minutes. The task times have as a mean value

of 2.3 minutes with a standard deviation of 2.9 minutes. Moreover, tasks can be performed in a maximum of 5 workstations. Furthermore, the model is solved with a conventional approach for Assembly Line Balancing and Worker Assignment (ALBWP) without consideration of trained workers and the reduction coefficient. In the conventional approach, it is assumed that we have just assembler workers with different skills (some of them are able to perform all tasks and others not).

Table 2. The results of the applied model with and without consideration of trainer workers.

CT [min]	Cost	Number of trainer workers	Number of assembler workers	Number of Open stations	Station time
35	18.6	2	4	4	[34.904, 34.727, 34.959, 34.835]
	23	0	5	5	[34.918, 34.908, 34.377, 34.897, 34.939]
40	17.3	1	4	4	[39.872, 38.774, 39.989, 39.581]
	20	0	5	5	[33.603, 39.391, 39.669, 36.656, 37.956]
45	14.6	2	3	3	[44.62, 44.453, 43.863]
	16	0	4	4	[44.89, 44.418, 44.994, 44.968]
50	13.3	1	3	3	[49.858, 49.973, 49.963]
	16	0	4	4	[45.995, 43.145, 49.737, 44.922]
55	13.3	1	3	3	[54.378, 54.638, 51.904]
	16	0	4	4	[46.972, 41.824, 54.255, 46.23]
60	12	0	3	3	[59.732, 59.883, 59.154]
	12	0	3	3	[59.678, 59.942, 59.84]

Table 2 indicates the results of solving the model with and without consideration of trainers, respectively. The number of occupied stations, the number of trainers and assemblers, and finally the station times can be seen in Table 2.

The differences between the two models are significant in term of costs with the only exception of the instance with a cycle time of 60 minutes since results are equals for costs and workers assignment. For all other cases, a trainer or both are involved in helping some workers. Thanks to trainers the time among stations is more balanced despite the traditional ALBWP. Moreover, with our model the assembly process can be executed in the same cycle time in a lower number of workstations and consequently lower cost, and this represents a good achievement for companies.

Finally, we can see that in the case where only assemblers are assigned to stations to perform tasks (for example when the cycle time is 60), then cost for both traditional ALBWP and the model here proposed is similar. Moreover, station time differs just a bit. It is mainly due to the fact that for higher cycle time workers with some experience levels are preferable to inexperience ones since they might not require support from trainers. Moreover, even if they might require more time in executing some tasks the station time is enough to avoid the trainer involvement.

5 Conclusions

In this paper, we have proposed a linear programming model that assigns tasks to workstations and workers according to the time and their level of experience. With this model, we aim to minimize the total cost of an assembly line that includes the salary of the workers as well as the cost of each workstation. To improve the assembly line performance, we assume that highly skilled workers, called trainers, might be involved in helping inexperienced ones. In such a way, less-skilled workers can learn from trainers and station time might be reduced. The model here proposed is helpful for practitioners who face a high employees' turnover and need fast training for all new workers involved in the assembly phase to avoid efficiency reductions. We apply our model to a real case assembly line and we compare our results with those obtained with a traditional approach for assembly line balancing and worker assignment problem. Results are very promising since the use of trainers in the line help to not only reduce the cost in comparison to the traditional line but also to reduce the maximal workstation time creating an important potential for increasing the line throughput and efficiency. On the other hand, in this case, we can support ageing and experienced workers by involving them in training activities and preventing them from the excessive physical workload. For future research the effect of learning and accumulated experience can be added as expressed by previous studies [18,19] Furthermore, numerical experiments, the model will be tested on a large benchmark of problem instances to assess more precisely its behavior and performances. Since the problem is NP-hard by extension of simple assembly line balancing problem, large instances might not be solved in a reasonable amount of time and consequently, heuristic approaches will be developed to tackle such instances. Finally, a sensitivity analysis will be carried out to investigate better the impact of different parameters of the problem on the final result.

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