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Considering physical workload and workforce diversity in a Collaborative Assembly Line Balancing (C-ALB) optimization model.

Ali Keshvarparast*, Olga Battaia, Amir Pirayesh**, Daria Battini***

** Department of Management and Engineering, University of Padua, Stradella San Nicola 3, 36100 Vicenza, Italy (e-mail: ali.keshvarparast@phd.unipd.it, daria.batiini@unipd.it).*

*** KEDGE Business School Bordeaux, France (e-mail:olga.battaia@ kedgebs.com, amir.pirayesh@ kedgebs.com)*

Abstract: In comparison to the traditional usage of robots, Cobotization (Human-Robot collaboration) can be considered as an effective way to increase the productivity of assembly lines while ensuring job security and flexibility. However, successful implementation of human-robot collaboration scenarios requires adapted decision support tools. Workforce diversity can be mentioned as one of the factors that should be included to study its impact on both the performance of the production system and on ergonomics. Accordingly, in this research, a new bi-objective optimization model for the collaborative assembly line with Cobots is proposed to simultaneously minimize the cycle time and the physical workload of human operators. The workforce diversity of human operators is modeled through experience level and physical ability. To analyze the benefits of the developed model, a comparison between the different solutions from the Pareto front is conducted. The results show that the utilization of Cobots can reduce both cycle time and physical workload in the assembly line.

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Keywords: collaborative assembly line, ergonomic, workers diversity, industry 4.0.

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1. INTRODUCTION

Today, customer needs are constantly evolving, and mass-production is being gradually replaced by mass-customization. Therefore, flexibility is considered one of the most valuable characteristics of production systems and especially of assembly lines (Kim et al. 2020). In this regard, as one of the main pillars of Industry 4.0, collaborative assembly lines with Cobots have been introduced as a solution to increase flexibility and reduce the physical workload for human operators (Boschetti et al. 2021). Cobots are robots that can work with human operators in a shared space, while direct interaction is not always required.

In the early phases of Cobots' introduction, the majority of research was related to how to design better Cobots (Rodríguez-Guerra et al. 2021). Improving the productivity and safety of Cobots was indeed the priority of researchers (Gualtieri et al. 2021). Recently, the optimization of Cobots implementation and integration in assembly lines has been given more attention (Weckenborg et al. 2020), particularly by considering the Human-Cobot symbiosis. Current studies indicate that despite the increase of Cobotization, most of the tasks are still performed by workers in the collaborative assembly line of customized products (Zennaro et al. 2019). Therefore, considering human factors such as workers' experience and physical capacity not only can improve the line performance (e.g., cycle time), but also can help industries to have a more ergonomic work environment (Katiraee et al. 2021). Particularly, in the line balancing problem, ignoring the workforce diversity can result in either non-optimal scenarios or tasks assigned to workers (but not to the Cobot) that cannot be handled or can endanger the worker's health. However, this factor has not been yet addressed in the Cobot context.

In order to bridge this gap, in this research, a bi-objective Mixed-Integer Linear model has been developed to optimize the line balancing in collaborative assembly lines with Cobots. The objective is to minimize the Cycle Time and the total physical workload for human operators. We consider three different types of human-Cobot interaction. These different types not only can be used in different stations but also can be used simultaneously in a single station. The worker diversity is modeled based on experience and physical ability.

The paper is organized as follows. In section 2, a brief literature review of research related to the collaborative assembly line and workers' diversity is provided. Section 3 describes the problem definition and explains the mathematical model formulation. Section 4 provides the results of numerical experiments. Ultimately, Section 5 presents conclusions and future work directions.

2. LITERATURE REVIEW

This section reviews the main recent studies related to collaborative assembly lines and worker diversity.

2.1 Collaborative assembly line balancing

As mentioned in the introduction, recently, there is more focus on the improvement of the Cobots' implementation in the production systems. This has been done in some cases by studying and adapting the classical problems, such as line balancing or task assignment to the new context. Michalos et al. (2018) proposed a framework to solve the problem of task

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assignment between humans and Cobots. They considered productivity, ergonomics, process quality, and layout efficiency as the performance factors for comparing the different layouts. Bruno and Antonelli (2018) and Antonelli and Bruno (2019) also proposed frameworks for task allocation between humans and Cobots in a collaborative station. In these works, task characteristics (task types such as tool retrieval, inserting clamp, welding, and fixing support) are considered but human factors are not addressed. Several other studies also proposed frameworks for improving the performance of collaborative assembly lines, such as Malik and Bilberg (2019), Huang et al. (2019), and Cohen (2021). None of these studies considered human factors.

The Collaborative Assembly Line Balancing (C-ALB) problem was introduced by Weckenborg & Spengler (2019). They studied the collaborative assembly line based on a two-sided assembly line problem. They proposed a cost-oriented mathematical model and considered energy expenditure as an ergonomic factor in constraints. Vieira et al. (2021) developed a two-level MILP model. By using a discrete-event simulation model they guaranteed that capacity-feasible solutions at the scheduling level will be accessible. As the objective function, they considered cost of using Cobots, workers, and production. A bi-objective mathematical cost-oriented collaborative assembly line model and a metaheuristic approach to solve the suggested model were proposed by (Li et al., 2021) with the objective of minimizing the cycle time and the implementation and production costs.

2.2 Worker diversity in assembly line

Carnahan et al. (2001) presented one of the first approaches which considered the physical demand of each task for workers in assembly context. Since then, several studies have included human factors and ergonomics aspects in line balancing such as physical capacity, fatigue, etc. (Battini et al. 2020). Battaïa and Dolgui considered the link between workers' performance, such as task completion time, and their experience, age, and physical capability in their work (Battaïa and Dolgui, 2013).

Katiraee et al. (2021) studied the impact of workers' experience on the outcome of the assembly line design. Besides experience, another prominent criterion that can distinguish workers and impact the task time is the supposed physical workload capacity. Gräßler et al (2021) studied the impact of human factors, such as experience, learning and forgetting, the age and the accordance of assembly operations on the task scheduling in a Manual AL. Dalle Mura & Dini (2019) assert that each worker has physical workload limitations. They ensure that assigned tasks' energy expenditure for each worker should not pass the physical workload limitation of the worker.

Several other examples can be found in the recent literature which indicates an increase in the integration of workers' diversity, specifically the variation of task time and physical capacity, in assembly-line studies. However, to the best of our knowledge, this factor has not yet been studied in collaborative assembly lines that include Cobots. To bridge this gap, in this paper, worker diversity is considered. It is important to mention that to measure the physical workload of each task, the well-known Borg scale method was applied (Borg, 1990). The scores range from 6 (minimum effort) to 20 (maximal effort). For each task, all the workers are asked to submit a score. The workers' physical status and physical workload limitations will be assessed for each worker based on the score they received from their self-assessment.

Comparing to the previous studies in the C-ALB context, the main contributions of this study are about the consideration of workforce diversity based on skill level and physical capacities and all possible collaboration scenarios simultaneously in a mathematical and optimization model.

3. PROBLEM DEFINITION

In a Collaborative Assembly Line (C-AL), resources (workers and Cobots) can be assigned to a station in two different ways: Indirect collaboration: only a Cobot assigned to a station, and Direct collaboration: a Worker and one or several Cobots are assigned to the same station. The latter situation can be itself performed in three modes: 1) Sequential: worker and Cobot accomplish the assigned tasks according to a given sequence and cannot do their task in parallel; 2) Simultaneous: worker and Cobot accomplish the assigned tasks in parallel; and 3) Supportive: worker and Cobot accomplish the assigned task by working together on the task (see Figure 1) (Zhang et al., 2021).

The main assumptions of the model are listed below:

- All the collaborative scenarios can be used.
- There is only one product, and the precedence relation tasks are known in advance.
- Time and physical workload of each task are deterministic and known in advance.
- Workers have three different experience levels (low-, medium-, and high-experienced).
- Higher experience means a shorter task completion time.
- Each worker has a limited physical capacity.
- The number of available Cobots is limited and they all have the same performance.
- It is not possible to assign a worker to a task for which the required task's physical workload is higher than the worker's physical capacity.

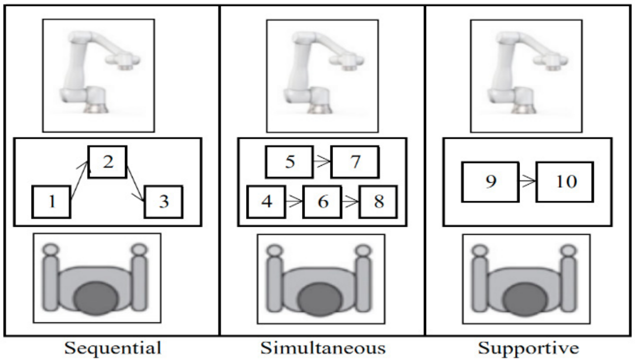

Figure 1. Human-Cobot Collaboration scenarios.

- Loading and unloading times for both workers and Cobots are neglectable and are not considered.
- It is not necessary to assign all the workers to the assembly line.

3.1 Model formulation

Considering the aforementioned assumptions, the C-ALB problem is modeled as a bi-objective Mixed-Integer Linear Programming (MILP) model. The two objective functions minimize the Cycle Time (CT) (see equations 23 to 28), to enhance the line productivity and the TMPW (Total Maximum Physical Workload of assigned workers) to improve the line ergonomics (see equation 29). The maximum workload is calculated based on the Borg score.

In the following, the model notations are presented:

Sets, indexes, and parameters:

I	Set of tasks
i, j	Tasks' indexes, $i, j = 1, \dots, I$
H	Set of workers
h	Workers' index, $h = 1, \dots, H$
C	Set of Cobots
c	Cobots' index, $c = 1, \dots, C$
S	Set of stations
s	Stations' index, $s = 1, \dots, S$
TP	Set of tasks precedencies
T_{ih}^{h}	Completion time of task i when assigned to worker h
T_{i}^{c}	Completion time of task i when assigned to Cobot
T_{ih}^{hc}	Completion time of task i when assigned to worker h and Cobot in supportive mode
PW_{ih}	Physical workload of task i for worker h
MPW_{h}	Maximum physical workload capacity of worker h
$bigM$	A very large positive number

Decision Variables:

X_{ihs}^{h}	1= if task i is assigned to worker h in station s; 0= otherwise.
X_{ics}^{c}	1= if task i is assigned to Cobot c in station s; 0= otherwise.
X_{ihcs}^{hc}	1= if task i is assigned to both worker h and Cobot c (supportive mode) in station s; 0= otherwise.
W_{ijh}^{h}	1= if task j should be done after task i by worker h; 0= otherwise.
W_{ijc}^{c}	1= if task j should be done after task i by Cobot c; 0= otherwise.
Y_{hs}^{h}	1= if worker h is assigned to station s; 0= otherwise.
Y_{cs}^{c}	1= if Cobot c is assigned to station s; 0= otherwise.
ST_{i}	Start time of task i
FT_{i}	Finish time of task i
SCT_{s}	Cycle Time of station s
CT	Cycle Time
$TMPW$	Total Maximum Physical Workload of assigned workers

Mathematical model:

$$Minimize\ CT \tag{1}$$

$$Minimize\ TMPW \tag{2}$$

Subject to:

$$\sum_{h}^{H}\sum_{s}^{S} X_{ihs}^{h} + \sum_{c}^{C}\sum_{s}^{S} X_{ics}^{c} + \sum_{h}^{H}\sum_{c}^{C}\sum_{s}^{S} X_{ihcs}^{hc} = 1 \quad , \forall\, i \in I \tag{3}$$

$$\sum_{s}^{S} Y_{hs}^{h} \le 1 \quad , \forall\, h \in H \tag{4}$$

$$\sum_{s}^{S} Y_{cs}^{c} \le 1 \quad , \forall\, c \in C \tag{5}$$

$$\sum_{h}^{H} Y_{hs}^{h} \le 1 \quad , \forall\, s \in S \tag{6}$$

$$\sum_{c}^{C} Y_{cs}^{c} \le 1 \quad , \forall\, s \in S \tag{7}$$

$$X_{ihs}^{h} + \sum_{c}^{C} X_{ihcs}^{hc} \le Y_{hs}^{h} \quad , \forall\, i \in I, h \in H, s \in S \tag{8}$$

$$X_{ics}^{c} + \sum_{h}^{H} X_{ihcs}^{hc} \le Y_{cs}^{c} \quad , \forall\, i \in I, c \in C, s \in S \tag{9}$$

$$\begin{aligned} \sum_{h}^{H}\sum_{s}^{S} X_{ihs}^{h} \times s + \sum_{c}^{C}\sum_{s}^{S} X_{ics}^{c} \times s + \sum_{h}^{H}\sum_{c}^{C}\sum_{s}^{S} X_{ihcs}^{hc} \times s \\ \le \sum_{h}^{H}\sum_{s}^{S} X_{jhs}^{h} \times s + \sum_{c}^{C}\sum_{s}^{S} X_{jcs}^{c} \times s \\ + \sum_{h}^{H}\sum_{c}^{C}\sum_{s}^{S} X_{jhcs}^{hc} \times s \\ , \forall (i, j) \in TP \end{aligned} \tag{10}$$

$$\sum_{i}^{I}\sum_{j}^{I} W_{ijh}^{h} = \sum_{i}^{I}\sum_{s}^{S} X_{ihs}^{h} + \sum_{i}^{I}\sum_{c}^{C}\sum_{s}^{S} X_{ihcs}^{hc} - 1 \quad , \forall\, h \in H \tag{11}$$

$$\sum_{i}^{I}\sum_{j}^{I} W_{ijc}^{c} = \sum_{i}^{I}\sum_{s}^{S} X_{ics}^{c} + \sum_{i}^{I}\sum_{h}^{H}\sum_{s}^{S} X_{ihcs}^{hc} - 1 \quad , \forall\, c \in C \tag{12}$$

$$W_{ijh}^{h} \le \frac{\left(\sum_{s}^{S} X_{ihs}^{h} + \sum_{s}^{S} X_{jhs}^{h} + \sum_{c}^{C}\sum_{s}^{S} X_{ihcs}^{hc} + \sum_{c}^{C}\sum_{s}^{S} X_{jhcs}^{hc}\right)}{2}, \quad \forall\, i, j \in I, h \in H \tag{13}$$

$$W_{ijc}^{c} \le \frac{\left(\sum_{s}^{S} X_{ics}^{c} + \sum_{s}^{S} X_{jcs}^{c} + \sum_{c}^{C}\sum_{s}^{S} X_{ihcs}^{hc} + \sum_{c}^{C}\sum_{s}^{S} X_{jhcs}^{hc}\right)}{2}, \quad \forall\, i, j \in I, c \in C \tag{14}$$

$$W_{iih}^{h} = 0 \quad , \forall\, i \in I, h \in H \tag{15}$$

$$W_{iic}^{c} = 0, \quad \forall\, i \in I, c \in C \tag{16}$$

$$\sum_{j}^{I} W_{ijh}^{h} \le 1 \quad , \forall\, i \in I, h \in H \tag{17}$$

$$\sum_{j}^{I} W_{ijc}^{c} \le 1, \quad \forall\, i \in I, c \in C \tag{18}$$

$$\sum_{i}^{I} W_{ijh}^{h} \leq 1, \quad \forall\, j \in I, h \in H \tag{19}$$

$$\sum_{i}^{I} W_{ijc}^{c} \leq 1, \quad \forall\, j \in I, c \in C \tag{20}$$

$$W_{ijh}^{h} + W_{jih}^{h} \leq 1, \quad \forall\, j \in I, h \in H \tag{21}$$

$$W_{ijc}^{c} + W_{jic}^{c} \leq 1, \quad \forall\, j \in I, c \in C \tag{22}$$

$$ST_i = 0, \quad \forall\, i = 1 \tag{23}$$

$$ST_j \geq FT_i, \quad \forall (i,j) \in TP \tag{24}$$

$$ST_j \geq FT_i - bigM * \left(1 - \sum_{h}^{H} W_{ijh}^{h} - \sum_{c}^{C} W_{ijc}^{c}\right), \quad \forall\, i,j \in I \tag{25}$$

$$\begin{aligned} FT_i \geq\; & ST_i + \sum_{h}^{H}\sum_{s}^{S} X_{ihs}^{h} * T_{ih}^{h} + \sum_{c}^{C}\sum_{s}^{S} X_{ics}^{c} * T_{i}^{c} \\ & + \sum_{h}^{H}\sum_{c}^{C}\sum_{s}^{S} X_{ihcs}^{hc} * T_{ih}^{hc}, \\ & \forall (i,j) \in TP \end{aligned} \tag{26}$$

$$\begin{aligned} SCT_s \geq\; & FT_i - ST_j - bigM * (1 - \sum_{h}^{H}\sum_{s}^{S} X_{ihs}^{h} \\ & - \sum_{c}^{C}\sum_{s}^{S} X_{ics}^{c} - \sum_{h}^{H}\sum_{c}^{C}\sum_{s}^{S} X_{ihcs}^{hc}) \\ & - bigM * (1 - \sum_{h}^{H}\sum_{s}^{S} X_{ihs}^{h} \\ & - \sum_{c}^{C}\sum_{s}^{S} X_{ics}^{c} \\ & - \sum_{h}^{H}\sum_{c}^{C}\sum_{s}^{S} X_{ihcs}^{hc}), \quad \forall\, i,j \in I, s \in S \end{aligned} \tag{27}$$

$$CT \geq SCT_s, \quad \forall\, s \in S \tag{28}$$

$$\sum_{i}^{I}\sum_{h}^{H} X_{ihs}^{h} \times PW_{ih} \leq TMPW \;, \forall\, s \in S \tag{29}$$

$$X_{ihs}^{h} \times PW_{ih} \leq MPW_h \;, \forall\, h \in H \tag{30}$$

Equation 3 guarantees that each task is assigned to one worker, to one Cobot or to a worker and Cobot in the same station. Equations 4 and 5 prevent the assignment of a worker or a Cobot to more than one station. Equations 6 and 7 determine that a maximum of one worker or one Cobot should be assigned to each station, respectively. Equations 8 and 9 calculate Y_{hs}^{h} and Y_{cs}^{c} (assignment of the resources to stations). Equation 10 assures that task precedence is respected. Equations 11 and 12 ensure that model assigns the correct number of sequence relations in each station. Equations 13 and 14 guarantee that if both tasks i and j were assigned to a worker or Cobot, W_{ijh}^{h} and W_{ijc}^{c} should become equal to one. Equations 15 to 22 assure that no binary, loop, or sub-tour will happen in tasks' sequence determination. Equation 23 ensures that the first dummy task, task one, will start at the beginning of the time horizon. Equation 24 guarantees that the start time of task j will be greater that the end time of task i if task j have a direct precedence with task i and equation 25 if task j was assigned after task i by tasks sequence (W^{h}, W^{c}). Equations 26 to 28 calculate respectively the finish time for each task, the cycle time for each station, and the CT. Equation 29 calculate the $TMPW$. Finally, equation 30 guarantees that the assigned tasks to each worker have a lower physical workload than the worker's limitation

4. NUMERICAL ANALYSIS

In this section, the results of numerical tests on the model using a real assembly line from an automotive industry are presented. The assembly of a vehicle front-end has been chosen to demonstrate the efficacy of a collaborative assembly line for assisting employees in handling heavy components that need higher physical effort than usual. In this case, there are 29 tasks, 6 workers (2 workers in each experience level), 2 Cobots, and 4 stations. Tasks' precedencies and times are included in Table 1. To solve the bi-objective mathematical model, epsilon constraint approach is used. This way, instead of a single optimal solution, there will be several non-dominated solutions creating a Pareto front. The case was solved using GAMS 28.0.1 on a standard computer with AMD Ryzen 7 4800H, 2.90 Ghz, and 16GB RAM.

Table 1. Tasks' precedence and time

Tasks	Prec.*	Worker ** (min)			Cobot (min)	Worker + Cobot (min)		
		L	*M*	*H*		*L*	*M*	*H*
1	-	0.58	0.49	0.4	-	0.5	0.42	0.35
2	-	0.58	0.49	0.4	-	0.5	0.42	0.35
3	1	0.44	0.37	0.3	-	-	-	-
4	2	0.44	0.37	0.3	-	-	-	-
5	-	0.58	0.49	0.4	-	0.51	0.43	0.36
6	-	0.58	0.49	0.4	-	0.51	0.43	0.36
7	5	0.54	0.46	0.38	0.45	-	-	-
8	6	0.54	0.46	0.38	0.45	-	-	-
9	7,8	2.22	1.88	1.55	-	2.1	1.78	1.47
10	-	0.69	0.58	0.48	-	0.61	0.52	0.43
11	-	0.65	0.55	0.45	0.6	-	-	-
12	10	0.38	0.32	0.26	0.35	-	-	-
13	11	0.98	0.83	0.68	0.85	-	-	-
14	11	0.98	0.83	0.68	0.85	-	-	-
15	11	0.64	0.54	0.45	-	-	-	-
16	11	0.54	0.45	0.38	-	-	-	-
17	14	0.64	0.54	0.45	-	-	-	-
18	13	0.64	0.54	0.45	-	-	-	-
19	13,14	0.94	0.79	0.66	-	-	-	-
20	3,4,9	1.65	1.4	1.15	1.56	1.47	1.25	1.03
21	20	0.70	0.56	0.49	-	0.62	0.53	0.43
22	20	1.20	1.02	0.84	-	1.14	0.97	0.80
23	20	0.69	0.58	0.48	0.6	-	-	-
24	20	1.42	1.2	0.99	-	-	-	-
25	20,16	0.62	0.52	0.43	-	0.57	0.48	0.4
26	25	0.90	0.73	0.63	-	0.81	0.69	0.57
27	22	0.87	0.73	0.61	0.79	-	-	-
28	22	1.69	1.43	1.18	-	-	-	-
29	27	1.43	1.21	1	-	1.35	1.15	0.94

* *Task precedence*

** *L, M, H: Low-, Medium-, High-Experienced*

4.1 Analysis of Cobots usage

To clarify the impact of Cobots on the performances of the assembly line, the same case was solved with and without Cobots (Collaborative AL and Manual AL). For the Manual AL, we considered that zero Cobot was available. The obtained results are shown in Figure 2. It can be observed that the use of Cobots can be beneficial for both productivity and ergonomics factors, being the cycle time and maximum physical load in the case.

It is also worth mentioning that in the case study, the Cobot alone or the Human-Cobot supportive mode is not always more performant than a single worker in terms of task completion time (see Table 1). Therefore, although it is expected to observe that using Cobots reduces the physical load of the assigned workers, the reduction of the cycle time could not be guaranteed. This situation can be also explained by the fact that the Cobots can perform some tasks in parallel with workers which reduces the cycle time in the assembly line. The same situation happened for TMPW. The Model assigned the tasks that have the higher physical workload to Cobots, so by using Cobots, this indicator can be significantly reduced.

4.2 Analysis of workforce physical capacity

The behavior of the model facing the changes in the workload capacity of the workers was studied. The results show that when the physical workload capacity is reduced (e.g., by changing or reforming the workforce), Manual assembly lines may hardly find a solution (see Fig. 3).

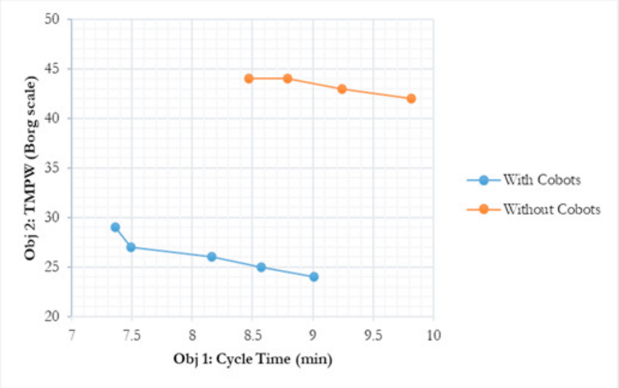

Figure 2. Pareto front of TMPW vs. CT in C-AL and Manual AL

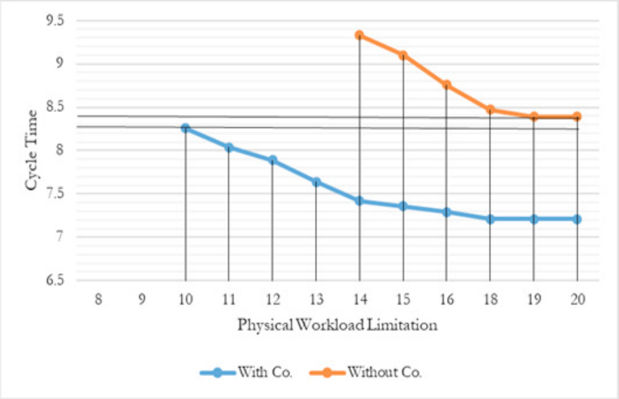

Figure 3. CT vs. workers' physical workload capacity

As illustrated in Figure 3, when the workforce has a lower physical workload capacity, using Cobots can be a good solution to cover the lack of more capable workers while this can also allow reducing the cycle time. In addition, Figure 3 shows that the lowest cycle time for the Manual AL, when there are highly capable workers in the assembly line, is nearly equal to the worst cycle time for C-AL, which is related to the lowest physical capacity of workers.

4.3 Analysis of assigned workforce experience

As the last step, by considering cycle time equal to 8.5 min we observed how Manual AL and C-AL managed the use of experienced workers. The obtained results (see Table 2) show that under the same cycle time limit, it is possible to use less experienced workers in C-AL (only low-experienced workers were used) compared to Manual AL where 2 high- and 2 medium-experienced workers were used.

Table 2. Skill level of assigned workers to each station

		Stations			
		1	**2**	**3**	**4**
Skill level	With Cobots	*low*	*low*	*low*	*low*
	Without Cobots	*high*	*medium*	*medium*	*high*

5. CONCLUSIONS

In this study, a new bi-objective linear programming model is proposed for the C-ALB problem to reduce the line cycle time and the maximum physical workload in each station, being common line efficiency and ergonomics indicators. In the proposed model, Human-Cobot collaboration scenarios are included in a more comprehensive way extending the models available in the literature, particularly by integrating the supportive model where the resources are in closer interaction. In addition, workforce diversity has been integrated into the model with a focus on experience and workload capacity. An industrial problem instance of relatively small size has been successfully solved in a reasonable time. To study the applicability of the model, some major managerial hypotheses, mainly around the Cobotization (or Manual assembly) and workforce formation decisions and their impact on the line performance, were studied. Our observations can be summarized as follows: i) The use of Cobots allowed reducing the cycle time and the maximum physical load at the same time; ii) using Cobots was a good decision when the workforce had a low physical capacity and it can be economically justified since it even allows reducing the cycle time; and iii) compared to Manual assembly, in case of Cobotization it was possible to assign less experienced workers with the same cycle time.

Although the above observations approve some global hypotheses, in the next step, comparing the proposed model with the already existing models should be studied. also, the human-related factors, as well as the capacity of the Cobot in coping with the human diversity, can be further studied. For instance, the cognitive workload can be also considered as a relevant factor. Also, investigating the Learning or Forgetting curves for collaboration assembly lines should be considered.

Moreover, the model can be enriched in terms of degrees of worker experience or workload capacity or with additional parameters. However, since the problem is NP-Hard, developing a more complex model or its application on big-size problems would heuristic or metaheuristic approaches.

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