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Enhancing inclusion of workers with disabilities in manufacturing: a human-robot collaborative assembly line balancing optimization model

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Abstract: Human-centered technologies play a key role in the Industry 5.0 paradigm and can be the driver for greater diversity, equity and inclusion. This study explores the potential of cobots to promote the inclusion of workers with physical disabilities. Existing research on disability inclusion in manufacturing mainly focuses on sheltered workshops and manual assembly lines. Here, a Constraint Programming optimization model is proposed to balance a human-robot collaborative assembly line that includes workers with disabilities. Specifically, this research explores how cobots can support or complement workers facing task incompatibilities or longer execution times with a multi-objective approach considering cycle time, inclusivity, costs, and incentives. The findings show that when considering workers with same level of disability (i.e., same incompatibility ratio), but with different capabilities, the personal characteristics have a significant impact in a manual environment, while cobots help maintain line performance reducing the effect of individual abilities. However, this benefit comes with higher unit costs. The main contribution of this study is to elucidate the role of cobots in the trade-off between operational performance and inclusivity.

Keywords: Industry 5.0, human-centricity, social sustainability, disability, assembly line, human-robot collaboration.

1. INTRODUCTION

According to the International Labour Organization (ILO), approximately 15% of the world population lives with a significant disability, and these individuals face notably higher unemployment rates worldwide. This underscores the need for disability inclusion in the workplace, which should move beyond mere compliance to become a core focus for companies, embracing diversity equity and inclusion (DEI) principles. In production settings, advanced automation technologies play a critical role in the inclusion of workers with physical impairments (Rojas et al., 2024). Cobots are particularly effective, when combining human skills with the capacity to perform tasks that are either unsuitable or too demanding for humans (Scalera et al., 2024). This adaptability makes them particularly valuable for DEI initiatives involving workers with disabilities.

The role of technology in enhancing labor participation is recognized in the literature (e.g., Ivanov, 2023; Leng et al., 2023) and reflected in recent industrial policies like the industry 5.0 (I5.0) paradigm (European Commission, 2024). However, earlier research on cobots has primarily examined their impact on manufacturing system flexibility, ergonomic risks, and safety (Keshvarparast et al., 2025). Evidence of their potential to include workers with physical disabilities (DW) has been little explored, particularly regarding performance implications.

This study aims to advance the current understanding of using cobots to support workers with physical disabilities considering their personal capabilities, accounted by execution times based on the impairment, worker-task incompatibilities as well as higher rest allowances, and the hiring incentives. For cobots, we consider collaboration modes, performance, operational costs, and investment. We propose an optimization model based on constraint programming to balance a collaborative assembly line, with cobots compensating for worker-task incompatibility and extended execution times. We drew on literature from sheltered workshops and collaborative assembly lines.

Overall, the novelty of our work is to propose a model that focuses on inclusion of DWs in ordinary collaborative production settings by allowing line balancing depending on personal characteristics. This study theoretically illustrates that cobots help to maintain line performance depending on the number of DWs and task incompatibilities, allowing to accommodate different individual characteristics. Under this premise, we also provide useful information for management decision making by analyzing the costs of investing in and operating cobots (i.e., energy consumption of the robots).

2. LITERATURE REVIEW

This section presents recent works that more closely relate to the scope of our study. Two streams have been identified, with limited overlap.

First, the available models for DWs mainly consider sheltered workshops or a manual ordinary assembly line. Miralles et al. (2007) first presented and solved the assembly line worker assignment and balancing problem (ALWABP) for a sheltered workshop (SWD) with the objective of minimizing the cycle time. The model considered individual abilities and physical

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limitations to affect execution times and task incompatibilities, making some a priori assignments. Since then, researchers have presented several variants and extensions of the ALWABP, such as considering a job rotation scheduling (Costa and Miralles, 2009), including DWs in an ordinary assembly line through parallel workstations to compensate for higher task times, and collaborative workstations employing two operators with different abilities (Araújo et al., 2012; Araújo et al., 2015), or considering the mixed-model sequencing in SWDs (Cortez and Costa, 2015). In the context of a conventional assembly line, Moreira et al. (2015) proposed an assembly line worker integration and balancing problem (ALWIBP), which aims to minimize the additional workstations needed to integrate a few DWs in an ordinary context. None of the abovementioned models considered human-robot collaboration.

The second stream of assembly line optimization models focuses on collaborative assembly lines. The human-centric perspective of I5.0 has boosted research on cobots for improving productivity, while ensuring safety and reducing ergonomic risk of workers. Interestingly, as highlighted by a recent review (Keshvarparast et al., 2023), most models consider productivity as the main performance criterion and DEI performance has not been investigated so far. The design of these studies mainly aims at modeling different cobot-human collaboration scenarios. El Zaatari et al. (2019) identified four approaches: independent, sequential, simultaneous, and supportive. Some works have considered just one collaboration scenario, e.g., independent (Rabbani et al., 2020), sequential (Çil et al., 2020), simultaneous (Dimény et al., 2021), supportive (Samouei and Ashayeri, 2019). Other studies have considered multiple collaboration scenarios (Keshvarparast et al., 2022; Mao et al., 2024), analysing specific applications suitable depending on the setting. More recently, Keshvarparast et al. (2025) proposed an optimization model considering multiple collaboration scenarios and an individualized rest allowance. However, DWs' personal characteristics and limitations, as well as the related incentives have not been addressed yet. To the best of our knowledge, only Chutima and Khotsaenlee (2022) considered both the use of cobots and the inclusion of DWs presenting an optimization model for a U-shaped line, where each station is covered just by one working resource (the robot or the worker). However, no direct collaboration between workers and robots is considered in that work.

The literature shows a gap with respect to human-robot collaboration for the inclusion of workers with physical disabilities, considering personal capabilities, execution times and a rest allowance for each cycle. Thus, a novel model for line balancing is proposed tackling the opportunities of human-robot collaboration for enhancing the inclusion of DWs in assembly lines.

3. PROBLEM DEFINITION AND MODEL

The aim of this study is to investigate how cobots can support the inclusion of DWs, facilitating the line balancing and mitigating the possible throughput reduction. The initial state of the problem is a pre-existing manual assembly line configuration hosting workers without disabilities, defined as average workers (AWs).

When including DWs, some limitations must be considered with respect to AWs. These can be of two forms: task-worker incompatibilities, and higher task execution times. We thus considered two profiles. DW1 has some task-worker incompatibilities, but compatible tasks can be executed with AW's task times. This can be the case of an experienced worker who suffers from musculoskeletal conditions or a minor injury. Instead, DW2 is a worker with both task-worker incompatibilities and higher task execution times, e.g. in case of a more severe disability or impairment.

An additional element to consider for DWs is rest allowance, which helps reducing fatigue and is particularly important to maintain consistency and ensure well-being in case of health conditions (Abdous et al., 2023; Battini et al., 2022). The formula proposed by Price (1990) is used in several models of the literature to assess the rest allowance in assembly lines (e.g. Finco et al., 2020). Keshvarparast et al. (2025) adjusted it considering the maximum allowed workload based on workers characteristics; however, when including DWs, the execution of tasks requires increased times (specifically for DW2) that should be reflected in the allowed rest time. Empirical data to calculate individual-level terms based on DW characteristics are lacking. In our model the rest allowance, granted in every cycle, is thus calculated as a worker-specific percentage multiplied by the time the worker is actively involved in performing the station tasks.

When considering the possible application of cobots on the line, we assumed them to be adopted only in stations hosting a DW, in order to investigate this technology as a support for enhancing inclusion while keeping production performance. Two direct collaboration scenarios are considered here: sequential (cobot and worker perform the assigned tasks sequentially and independently with own assigned time), and supportive (worker and robot accomplish a task together, working interactively). The collaboration scenario and the worker's profile are crucial for task assignment since the execution time depends on the combination of these two factors. The collaboration scenario also determines robot speed, which must be limited in supportive mode (ISO/TS 15066:2016) and, consequently, the associated energy costs. Each task is associated with a specific execution mode, i.e., a task is performed by the worker, the cobot, or supportively. The transfer time, and the time needed to switch from two different execution scenarios are considered negligible.

Furthermore, yearly differential costs are considered with respect to the original configuration. Annualized investment involves purchasing and installation of cobots, while operational costs include energy consumption and maintenance costs. Institutional incentives granted for hiring DWs are also taken into account.

To solve this human-robot collaborative assembly line and worker integration balancing problem (HRC-ALWIBP) the following bi-objective model is proposed. The first objective function maximizes the inclusivity (1a), defined as the number of operators with disabilities working in the line (3). The second, is a hierarchical objective function (1b) which minimizes the cycle time as a first objective and, in case of a tie, the total differential cost of the line. Constraint Programming (Rossi et al., 2006) is adopted, which allows any type of equations, including nonlinear ones. Furthermore, the modelling phase takes advantage of global constraints and built-in functions, while the solving one of advanced search strategies, embedded in the efficient solvers continuously developed by the CP community.

Indexes, sets and parameters:

s	index for a station
i, j	index for tasks
w	index for a type of worker
c	index for execution scenarios
C_{cob}	set of execution modes involving a cobot
C_{hum}	set of execution modes with human involvement
$C[w]$	set of execution modes tied for worker type w
P	set of task precedencies, (i,j) where i precedes j
S	set of stations
T	set of tasks
$\alpha[w]$	% describing the rest time needed by worker w
$\mathrm{CM}[i, c]$	compatibility matrix, i.e. execution time of task i for execution mode c, where 0 means incompatibility
cc	annualized cobot investment cost
ep	energy cost
in	yearly incentive for hiring a DW
mc	yearly cobot maintenance cost
pc_c	cobot power consumption in scenario c
yh	yearly working hours

Decision and auxiliary variables:

CT	cycle time
INC	inclusivity
$W[s]$	array of station-worker type assignment
$Cobot[s]$	=1 if a cobot is assigned to station s; = 0 otherwise
$T[s]$	set of tasks assigned to station s
$Ex[i]$	the execution mode to perform task i
$CE[s]$	energy cost of station s
TC	total cost
$WT[s]$	human working time in station s
$RT[s]$	rest time required by the worker of station s
$SWT[s]$	working time of station s
$ST[s]$	total time of station s

Optimization model:

$$Maximize\ INC \tag{1a}$$

$$Minimize\ CT + \frac{TC}{BigM} \tag{1b}$$

$$partition\_set\ (\{T[s]\}_{s \in S}, T) \tag{2}$$

$$INC = count\ (s \in S \mid W[s] = (DW1 \vee DW2)) \tag{3}$$

$$(i\ \in T[s1]) \wedge (j \in T[s2]) \Rightarrow s1 \leq s2 \quad \forall (i, j) \in P \tag{4}$$

$$i \in T[s] \Rightarrow\ Ex[i]\ \in\ C\big[W[s]\big] \quad \forall s \tag{5}$$

$$CM\big[i, Ex[i]\big] > 0 \quad \forall i \in T \tag{6}$$

$$count(i \in T[s] \mid Ex[i] \in C_{cob}) \geq 1 \Rightarrow Cobot[s] = 1\ \forall s \tag{7}$$

$$count(i \in T[s] \mid Ex[i] \in C_{hum}) \geq 1 \quad \forall s \tag{8}$$

$$SWT[s] = \sum_{i \in T[s]} CM\big[i, Ex[i]\big] \quad \forall s \tag{9}$$

$$WT[s] = \sum_{i \in T[s]} (CM\big[i, Ex[i]\big] \mid Ex[i] \in C_{hum}) \quad \forall s \tag{10}$$

$$RT[s] = WT[s] \cdot \alpha\big[W[s]\big] \quad \forall s \tag{11}$$

$$ST[s]\ = \max\{SWT[s], WT[s] + RT[s]\} \quad \forall s \tag{12}$$

$$CT = \max\{ST[s]\}_{s \in S} \tag{13}$$

$$t_{seqR,s} = \sum_{i \in T[s]} (CM\big[i, Ex[i]\big] \mid Ex[i] = \mathrm{seqR}) \quad \forall s \tag{14}$$

$$t_{supp,s} = \sum_{i \in T[s]} (CM\big[i, Ex[i]\big] \mid Ex[i] = \mathrm{supp}) \quad \forall s \tag{15}$$

$$CE[s] = (t_{supp,s} \cdot \mathrm{pc}_{supp} + t_{seqR,s} \cdot \mathrm{pc}_{seqR} + (CT - t_{supp,s} - t_{seqR,s}) \cdot \mathrm{pc}_{standby}) \cdot \frac{\mathrm{yh}}{CT} \cdot \mathrm{ep} \quad \forall s \tag{16}$$

$$TC = \sum_{s \in S} CE[s] + Cobot[s] \cdot (\mathrm{cc} + \mathrm{mc}) - INC \cdot \mathrm{in} \quad \forall s \tag{17}$$

Constraint (2) exploits the global constraint *partition set* to create a partition of the original set of tasks among the stations of the line. As the tasks are performed in sequence, constraint (4) ensures that the task assignments respect the precedencies. Constraint (5) ensures that each task assigned to a station is performed in one of the execution scenarios compatible with the selected worker. Constraint (6) ensures that for every task assigned to a station, the chosen execution mode is permitted by the compatibility matrix (CM), i.e., the task time is greater than zero. By (7), thanks to the built-in *count* operator, a cobot is assigned to a station, only if at least one of the tasks is performed in a collaboration scenario involving the use of a cobot. Constraint (8) ensures that in each station at least one task is performed in an execution scenario with active involvement of the worker. The station working time (9) is the sum of the execution times to perform all the tasks assigned to the station. The human working time (10) is the sum of all task times in an execution mode in which the worker is actively involved. The rest time in each station (11) is calculated as a percentage α of the working time depending on the type of assigned worker. By (12) rest time is included into the station time, allowing overlapping with cobot sequential mode. The cycle time is then calculated by (13). Since in each collaboration scenario the cobot energy consumption is different, it is necessary to trace the total execution time, for each station, for cobot in sequential mode (seqR) and supportive (supp) (14-15). The annual energy cost per station (16) is determined multiplying each fraction of the cycle time spent in a specific collaboration scenario by the corresponding power consumption; and in turn by the number of cycles in a year and the energy cost, leading to a non-linear constraint. The total yearly cost is given by (17), involving operational and investment costs. The total energy cost is given by the sum of the energy costs of all stations. The total cost of cobots is the single annualized cost of purchasing and implementation plus the yearly maintenance cost, multiplied by the number of cobots in the line, while the total incentive for hiring DWs, is given multiplying the inclusivity by the institutional incentive.

4. ILLUSTRATIVE EXAMPLE AND RESULTS

The model was implemented in Minizinc (Nethercote et al., 2007) using the solver HiGH 1.7.2 (Huangfu and Hall, 2018) and it was run on an Intel® Core™ i7-14700 (2.10 GHz) 32 GB RAM computer with an average computational time of 17 seconds for the following illustrative example.

The proposed model is tested on the Jackson instance (Jackson, 1956), considering 11 tasks and the corresponding precedence diagram, and a fixed number of stations equal to five, which has an initial optimal cycle time of 10 minutes. For the input data, the following assumptions are made:

- Only one shift of 8 hours/day and 220 working days/year.
- A mandatory rest of 20% is adopted for DWs, based on the insights gained from the interviews with a specialized medical unit, which assesses work capabilities and limitations of DWs, i.e. $\alpha[W[s]]$ is set to 0% for AWs, and to 20% for DWs.
- The incompatibility ratios in scenarios involving cobots are considered as in Weckenborg et al. (2020) and assigned using a pseudo-random code. The task-worker incompatibility ratio was set to 5/11.
- The personal task times of DW2 were obtained increasing the task time of AWs by a factor based on data in Litwin et al. (2024). The execution times in collaboration scenarios were calculated using the factors discussed in Weckenborg et al. (2020): 0.7 time the personal task time of the operator for supportive mode, twice the AW's task time for seqR.
- The energy consumption of a UR5e cobot was considered (Universal Robots, 2023).
- The energy costs were taken from Eurostat (2024), while other cobot-related costs from Gualtieri et al. (2021), with an expected lifespan of 10 years and an interest rate of 5%.
- The Italian hiring incentive is accounted, which is a one-time grant of 12000€ for each DW hired.

Since the model would always prefer DW1 workers, who are less impacting on the line performance when giving the freedom to select among DW1s and DW2s, two separate situations were investigated: one including only DW1s, the other including only DW2s. The ε-constraint method is applied for multi-objective optimization, with and without cobots to observe the differences in production performance. In both situations the worst-case scenario is considered, as the workers in a set of runs have the same incompatibilities. Several comparable CMs (i.e., same compatibility ratio) were considered to highlight the impact of personal characteristics (see example in Table 1).

Table 1 Example of the structure of the CMs, times in minutes.

	AW	DW1	$DW1_{su}$	DW2	$DW2_{su}$	SeqR
Task 1	6.0	0	4.2	0	12.6	0
Task 2	2.0	0	1.4	0	4.2	4.0

4.2 Inclusion of DW1 workers

As highlighted in Fig. 1, for the reference case CM5, the throughput can be maintained when including one DW1 without a cobot. However, when a higher number of DW1s is employed in the line without cobots, the cycle time gradually increases up to 12 minutes with three DW1s. In this scenario, there is no feasible solution for four or five DW1s without cobots; this is mainly due to the incompatibilities and precedence constraints. The implementation of cobots, allows even to decrease the cycle time, as DW1s have the same execution times as AWs, but the supportive mode reduces them by 30%. In this scenario, it is possible to include up to four DW1s and the cycle time in all cases would be equal to or below 10 minutes. However, to sustain production performance with a higher number of DWs, a different number of cobots is required, which raises the cost of the line. For the reference case, the additional unit cost can be up to 1.97 €/unit, Fig. 1 highlights that for up to two DW1s the solutions are aligned, with and without cobots, regardless of the personal characteristics. However, with more than two DW1 out of five and without cobots, the personal incompatibilities have a relevant impact on performance, which progressively approaches the scenario of a sheltered workshop (Miralles et al., 2007). It is worth noticing that cobots have a significant role in mitigating the effect of personal limitations, as the production performance can be kept at the same level of the original line or even be improved, with an exception for four DW1s in the case of CM4.

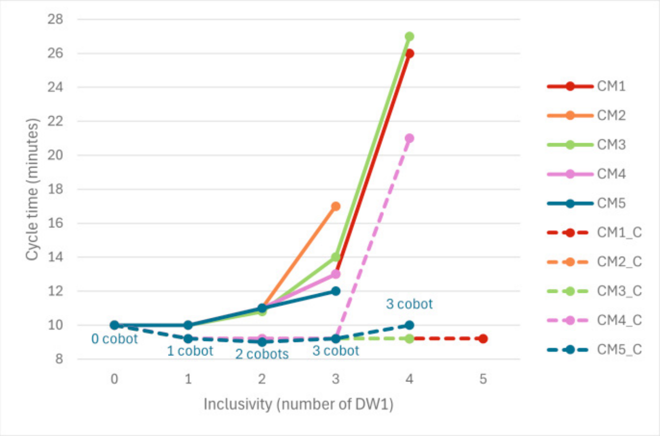

Fig. 1 Inclusion of DW1s with (dotted lines) and without cobots (plain lines) for different CMs. For CM5, the number of cobots is shown.

4.3 Inclusion of DW2 workers

The inclusion of DW2s has a higher impact on production performance compared to DW1 workers, due to the higher personal task times. As highlighted by Fig. 2, the optimal cycle time increases with the inclusion of just one DW2. Considering the reference case CM5, without cobots, as the number of DW2s to be included increases, the cycle time rises significantly up to 19 minutes. The implementation of cobots mitigates the increase in cycle time, allowing a balance between inclusivity and production performance. Considering CM5, the improvement with respect to the case without cobots, is of 8% for one DW2 worker and can be even of 20.5% with three DW2. Furthermore, cobots allow for a feasible solution also for four DW2s. Compared to the case of DW1s, personal characteristics have a significantly higher impact. In some cases, a higher number of cobots is required, impacting on the costs, and the increase in cycle time reduces the production volume; therefore, the impact on the unit cost can be much higher than the case of DW1s (e.g., with CM5, four DW2s and three cobots, the additional unit cost would be 3.69€/unit, not considering the augmented share of fixed costs).

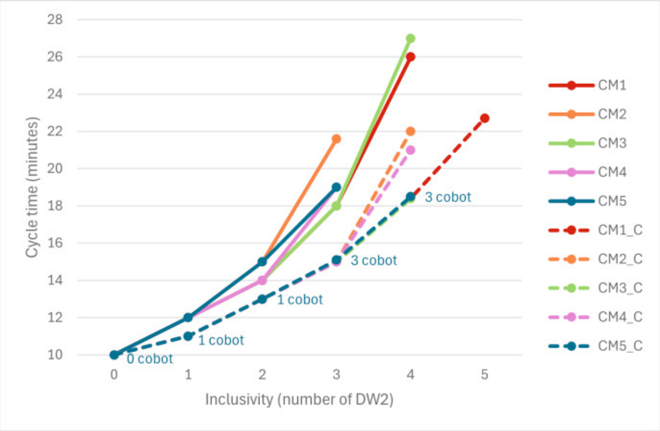

Fig. 2 Inclusion of DW2s with (dotted lines) and without cobots (plain lines) for different CMs. For CM5 the number of cobots is shown.

4.4 Cobot effect on the line balancing

The presence of cobots influences the line balancing. By running the model with different CMs, it was observed that with cobots the workload is distributed more evenly along the line than in the case without cobots, where AWs are charged with more work. Furthermore, the preferred collaboration scenario is the supportive one, as it allows to reduce the execution times and the cobots energy consumption, leading to lower energy costs in the objective function. Therefore, a consequence of the hierarchical function is to increase the direct involvement of the worker with disabilities. The task is assigned in sequential mode to the cobot just in the case of task-worker incompatibility, as well as to bridge the rest allowance avoiding an increase of the cycle time (see Fig. 3).

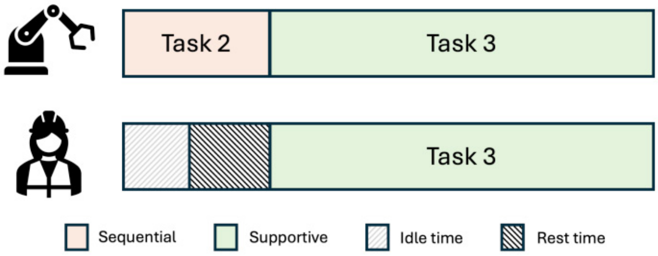

Fig. 3 Example of sequential mode assigned to the cobot to bridge the rest time.

5. CONCLUSIONS

This work presents an optimization model to balance an ordinary collaborative assembly line when including DWs, with the aim to evaluate how task-worker incompatibilities and personal execution times affect line performance and assess the role of cobots in mitigating this impact and in the line balancing. Results highlight that the personal characteristics of DWs, i.e., incompatibilities and task times, are determinant on the outcome, even when the incompatibility ratio is constant across scenarios. Nevertheless, across the various scenarios, cobots mitigate the increase in cycle time - similarly to the case when considering worker's age (Keshvarparast et al., 2025) - and standardize the outcomes for a given number of DWs, minimizing the variability in cycle times due to workers' diversity. Specifically, when only incompatibility is present (DW1s) cobots allow to maintain production performance while achieving greater inclusivity. For DW2s the impact on the line performance is more significant and closely tied to personal characteristics of the workers; cobots partially mitigate performance drop, thereby enhancing line inclusivity. However, from a cost perspective, even when introducing incentives (e.g., in this case, the ones connected to the Italian hiring policies), additional costs are present. While increased production volumes for DW1s could help balance costs in some scenarios, further fundings might be needed to make it economically viable for employers to hire DWs. These findings could guide policymakers in designing a better incentive strategy for the inclusion of DWs in manufacturing environments, based on the workers' profiles.

This paper contributes to the scientific debate by tackling the opportunity of implementing cobots for the inclusion of workers with disabilities, which is little explored even if it is a core value of I5.0. Despite the promising results, further research is needed to make the model suitable for real-life applications. First, since disability is a spectrum and personal characteristics are determinant for the outcome, future research should integrate personalized data based on individual characteristics to validate the results. Second, future research should explore collaboration impacts on execution times in case of DWs. The rest estimation should include ergonomic factors for all workers based on the personal characteristics and execution time (e.g. worker's energy expenditures and maximum allowed energy expenditure), while considering the mandatory rest and prescription of the specialized medical unit. Lastly, for real-case applications of larger-scale, different solving methods, such as heuristics, should be developed and tested, to reduce the computational times.

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REFERENCES

Abdous, M.A., Delorme, X., Battini, D., Berger-Douce, S. (2023) Multi-objective collaborative assembly line design problem with the optimisation of ergonomics and economics. *Int J Prod Res,* 61(22), 7830–7845.

Araújo, F.F.B., Costa, A.M., Miralles, C. (2012) Two extensions for the ALWABP: Parallel stations and collaborative approach. *Int J Prod Econ,* 140(1), 483–495.

Araújo, F.F.B., Costa, A.M., Miralles, C. (2015) Balancing parallel assembly lines with disabled workers. *Eur J Ind Eng,* 9(3), 344-365.

Battini, D., Berti, N., Finco, S., Zennaro, I., Das, A. (2022) Towards industry 5.0: A multi-objective job rotation model for an inclusive workforce. *Int J Prod Econ,* 250, 108619.

Chutima, P., Khotsaenlee, A. (2022) Multi-objective parallel adjacent U-shaped assembly line balancing collaborated by robots and normal and disabled workers. *Comput Oper Res,* 143, 105775.

Çil, Z.A., Li, Z., Mete, S., Özceylan, E. (2020) Mathematical model and bee algorithms for mixed-model assembly line balancing problem with physical human–robot collaboration. *Appl Soft Comput,* 93, 106394.

Cortez, P.M.C., Costa, A.M. (2015) Sequencing mixed-model assembly lines operating with a heterogeneous workforce. *Int J Prod Res,* 53(11), 3419–3432.

Costa, A.M., Miralles, C. (2009) Job rotation in assembly lines employing disabled workers. *Int J Prod Econ,* 120(2), 625–632.

Dimény, I., Koltai, T., Sepe, C., Murino, T., Gallina, V., Komenda, T. (2021) MILP model to decrease the number of workers in assembly lines with human-robot collaboration. *IFAC-PapersOnLine,* 54(1), 169–174.

El Zaatari, S., Marei, M., Li, W., Usman, Z. (2019) Cobot programming for collaborative industrial tasks: An overview. *Rob Auton Syst.,* 116, 162-180.

European Commission, Directorate-General for Research and Innovation (2024) *ERA Industrial Technologies Roadmap on Human-Centric Research and Innovation for the manufacturing sector*. Publications office of the European Union.

Eurostat (2024) Electricity prices for non-household consumers - bi-annual data (from 2007 onwards) *https://ec.europa.eu/eurostat/databrowser/view/nrg_pc_205__custom_12938202/default/table?lang=en.*

Finco, S., Battini, D., Delorme, X., Persona, A., Sgarbossa, F. (2020) Workers' rest allowance and smoothing of the workload in assembly lines. *Int J Prod Res,* 58(4), 1255–1270.

Gualtieri, L., Rauch, E., Vidoni, R. (2021) Methodology for the definition of the optimal assembly cycle and calculation of the optimized assembly cycle time in human-robot collaborative assembly. *Int J Adv Manuf Tech,* 113(7-8), 2369–2384.

Huangfu, Q., Hall, J.A.J. (2018) Parallelizing the dual revised simplex method. *Math Program Comput,* 10(1), 119–142.

ISO (2016) *Robots and robotic devices – Collaborative robots (ISO/TS 15066:2016).* ISO.

Ivanov, D. (2023) The Industry 5.0 framework: viability-based integration of the resilience, sustainability, and human-centricity perspectives. *Int J Prod Res,* 61(5), 1683–1695.

Jackson, J.R. (1956) A Computing Procedure for a Line Balancing Problem. *Manage Sci,* 2(3), 261–271.

Keshvarparast, A., Battaia, O., Pirayesh, A., Battini, D. (2022) Considering physical workload and workforce diversity in a collaborative assembly line balancing (C-ALB) optimization model. *IFAC-PapersOnLine,* 55(10), 157-162.

Keshvarparast, A., Battini, D., Battaia, O., Pirayesh, A. (2023) Collaborative robots in manufacturing and assembly systems: literature review and future research agenda. *J Intell Manuf,* 35(5), 2065-2118.

Keshvarparast, A., Katiraee, N., Finco, S., Calzavara, M. (2025) Integrating collaboration scenarios and workforce individualization in collaborative assembly line balancing. *Int J Prod Econ,* 279, 109450.

Leng, J., Zhong, Y., Lin, Z., Xu, K., Mourtzis, D., Zhou, X., Zheng, P., Liu, Q., Zhao, J.L., Shen, W. (2023) Towards resilience in Industry 5.0: A decentralized autonomous manufacturing paradigm. *J Manuf Syst,* 71, 95-114

Litwin, P., Antonelli, D., Stadnicka, D. (2024) Employing disabled workers in production: simulating the impact on performance and service level. *Int J Prod Res,* 62(12), 4530–4545.

Mao, Z., Sun, Y., Fang, K., Huang, D., Zhang, J. (2024) Balancing and scheduling of assembly line with multi-type collaborative robots. *Int J Prod Econ,* 271, 109207.

Miralles, C., García-Sabater, J.P., Andrés, C., Cardos, M. (2007) Advantages of assembly lines in Sheltered Work Centres for Disabled. A case study. *Int J Prod Econ,* 110(1-2), 187–197.

Moreira, M.C.O., Miralles, C., Costa, A.M.C. (2015) Model and heuristics for the assembly line worker integration and balancing problem. *Comput Oper Res,* 54, 64–73.

Nethercote, N., Stuckey, P.J., Becket, R., Brand, S., Duck, G.J., Tack, G. (2007) MiniZinc: Towards a Standard CP Modelling Language. In: Bessierè, C., *Principles and Practice of Constraint Programming – CP 2007*. Springer Berlin Heidelberg, Berlin, Heidelberg, 529–543.

Price, A.D.F. (1990) Calculating relaxation allowances for construction operatives-Part 1: Metabolic cost. *Appl Ergon.*, 21(4), 311-317.

Rabbani, M., Zeinab, S., Behbahan, B., Farrokhi-Asl, H., (2020) The Collaboration of Human-Robot in Mixed-Model Four-Sided Assembly Line Balancing Problem. *J Intell Robot Syst,* 100(1), 71–81.

Rojas, M., Balderas, D.C., Maldonado, J., Ponce, P., Lopez-Bernal, D., Molina, A. (2024) Lack of verified Inclusive Technology for Workers with disabilities in industry 4.0: a systematic review. *Int J Sustain Eng,* 17(1), 1-21.

Rossi, F., Van Beek, P., Walsh, T. (2006) *Handbook of Constraint Programming*. New York, Elsevier.

Samouei, P., Ashayeri, J. (2019) Developing optimization & robust models for a mixed-model assembly line balancing problem with semi-automated operations. *Appl Math Model,* 72, 259–275.

Scalera, L., Lozer, F., Geerinck, J., Breda, A., Totis, F., Polo, F., Giusti, A., Gasparetto, A. (2024) A Collaborative Robotics Application for the Assembly of Car Rear Lamps. In: *Lect Notes Netw and Syst*, 1125, 29–37.

Universal Robots (2023) *UR5e Technical Specification.*

Weckenborg, C., Kieckhäfer, K., Müller, C., Grunewald, M., Spengler, T.S. (2020) Balancing of assembly lines with collaborative robots. *Bus Res,* 13(1), 93–132.