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METHODS

# Developments in the literature and new study recommendations within the scope of the assembly line worker assignment and balancing problem (ALWABP)

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In this study, by defining the assembly line worker assignment and balancing problem (ALWABP), the point that has been reached to this day is researched on ALWABP. The studies in question are evaluated comprehensively in terms of their objective functions, established decision models, additional constraints that are being considered, the solution method that is applied, the size of the problem, the data that were used in the research, the type of assembly line that was used in the research, and the product model variety. For this purpose, a total of 41 articles, which are presented on the Web of Science (WoS), Scopus, and Google Scholar databases, are reviewed from the time that this problem first appeared in 2007, up to 2022. Keywords that are used while researching the mentioned databases are "assembly line worker assignment and balancing problem (ALWABP)", "Assembly Line Balancing Problem (ALBP)," and "Worker Assignment Problem (WAP)." Based on the articles examined in the study, the developments in the literature concerning the subject of ALWABP have been discussed, and the required study themes in this area have been determined. Since the research performed is a study that has not taken any place in the literature to this day, it is considered that it can shed light on the research that might be needed in the future in the ALWABP area.

**Keywords:** Assembly Line Balancing Problem, Worker Assignment Problem, worker heterogeneous, ALWABP, literature research

## Introduction

More use of production resources in order to reduce production costs is gaining more and more importance day by day in the market conditions where competition is increasing. This situation brings with it the tendency toward mass production. In mass production systems, the effective design of assembly lines has a very important place. The performance of the line design is provided by balancing the tasks' total time assigned to the workstations on these lines. According to this, the Assembly Line Balancing Problem (ALBP) is the assignment of the tasks to be performed to the stations in the line, depending on the product and production constraints, in a way to balance the workload between the stations. In this way, it is aimed to establish assembly lines that can achieve high quality with low production costs under standard production conditions (1). ALBP is defined as the tasks' assignment to sequential workstations in such a way as to optimize a performance criterion, given the tasks required to perform the assembly process, the duration of these tasks, and the precedence relations between them (2). In assembly lines designed to produce high volumes, the station capacity should be used at the highest level, and the total task time difference between workstations should be minimized.

ALBP was introduced by Salveson (3). Jackson (4), on the contrary, first developed a mathematical model for assigning tasks to workstations and obtained a solution using dynamic programming (DP) for an ALBP with task times. For the last

70 years, different methods have been tried to be developed both in production environments and in academic studies regarding the solution of the ALBP. The purpose of the ALBP is minimizing the number of stations to be opened along the line, usually for a determined cycle time (5). Accordingly, the assumptions considered in the ALBP are as follows (6).

1. All parameters are certainly known.
2. A task cannot be split between more than one station.
3. Tasks cannot be performed in an arbitrary order due to technological precedence requirements.
4. All tasks must be performed.
5. The stations have the necessary equipment and labour force to perform all the tasks.
6. Task times are independent of stations and previous/next tasks.
7. Any task can be done at any station.
8. An entire line is considered in series without a feeder or parallel sub-assembly line.
9. The assembly system is assumed to be designed for a unique model of a single product.
10. The cycle time is given and fixed.
11. The station number is given and fixed.

If there is a change in any of the first nine items, the problem turns into the General Assembly Line Balancing Problem (GALBP) (1). If the tenth item is determined to be an objective function of minimizing the cycle time, the Simple Assembly Line Balancing Problem-1 (SALBP-1) emerges. If the eleventh item is determined to be an objective function in the form of minimizing the number of stations, Simple Assembly Line Balancing Problem-2 (SALBP-2) is in question.

Assembly lines have an important place in the efficiency of production systems, and therefore the interest in line balancing is increasing day by day. However, when the literature is examined, it is seen that most of the studies have remained at the theoretical level, and very few studies have been carried out in practice. Although there are many reasons for this, one of the main reasons is the neglect of worker differences that occur during line balancing in practice. From this point of view, it is important to carry out studies in the field of balancing, in which worker dependency is ensured and the concept of "heterogeneous worker characteristics" is considered. Thus, it will be ensured that results are achieved with approaches compatible with real life. Studies carried out for this purpose are directly related to the problem of assigning workers. However, in the literature, the issue of assigning workers to assembly lines is examined under a separate heading and kept separate from the balancing problem. Industrial enterprises that want to achieve real efficiency and profitability should deal with the assignment and balancing problems of assembly lines together. Accordingly, in the study, the studies carried out in the literature within the scope of the Assembly Line Worker Assignment and Balancing Problem (ALWABP) were examined in detail. Additionally, the point reached in terms of development level was determined, and the studies that needed to be performed in future periods were emphasized. The reasons for focusing on ALWABP in the study can be explained as follows:

1) ALBP assumes that the task times are fixed, but in real life, each worker may complete the same task at different times due to the different abilities of each worker.
2) ALBP does not take into account that different completion times on the same task are due to the different performance level of each worker.
3) In ALBP, in cases where the worker has no knowledge about the task, it is not considered that he/she will not be able to perform the task at all.

The problem structure in which the above-mentioned conditions are considered is the Assembly Line Balancing and Worker Assignment Problem (ALBWAP), which has a structure closer to real-life production processes. In ALBWAP, the aim is not only to assign tasks to stations but also to assign workers to stations. Accordingly, different and more realistic constraints than ALBP are considered.

Assembly lines, where available resources are limited, these are the places where task completion times differ depending on the worker performing the task, and at the same time, some task-worker incompatibilities are experienced. This definition was first put forward by Miralles (6). ALWABP brings together two simultaneous solutions: the assignment of tasks to stations and the assignment of existing workers to stations (7). Miralles (6) stated that in some countries, practices called “Sheltered Work Centers for the Disabled-SWD” are allowed so that disabled people can start working life like other people. In these countries, it is believed that the treatment processes of the disabled are positively affected by enabling the disabled to exist in social life thanks to SWDs. The adoption of assembly lines in these centers provides many advantages. In SWDs, workers’ barriers become invisible as they are assigned tasks appropriate to them. By balancing the workload that is assigned to each worker at each station in the balancing processes carried out in SWDs, it is aimed at maximizing the line’s efficiency and considering and respecting the constraints of workers arising from their disabilities when assigning tasks to workers (6). Here, it is aimed to assign the workers to the workstations created on the assembly line in a way that will minimize the stations’ cycle time and establish the line balance of the stations in the best way possible. There are several assumptions for this problem structure (6):

1. The completion times of tasks and precedence relationships are determined.
2. Aseemblies are performed for only one product on the line.

3. A serial and straight line is defined, in which buffers are not considered.
4. Task times vary as workers have different abilities.
5. In general, there is no slow or speedy worker. Workers may be very slow or even unable to perform any task, but for any other task, they can be very fast and efficient.
6. Only one worker can be assigned to a station.
7. Each task is assigned to only one workstation, on the condition that the worker assigned for a task is able to carry out the task and that the precedence relations between the tasks are taken into account.

However, as in every problem structure, certain constraints are expected to be met in ALWABP (6):

1. Each task must be assigned to one workstation and one worker.
2. Each worker should be assigned to only one station and only one worker should be assigned to each station.
3. The precedence relationships of the tasks should be defined.
4. Stations should be able to assign more than one task as long as the cycle time ($C$) is not exceeded.
5. The number of stations to be established must be equal to or less than the number of workers.

After the basic assumptions and notations are stated, the most obvious case in SWD is that there must be specific workers who can complete each task in defined times and productivity must be increased on the line $C$ is the decision variable that represents the time that the workpiece can be processed by a station of the assembly line and is the inverse of the production rate (8). Therefore, maximizing efficiency means minimizing $C$. For this reason, it was desired to focus on solutions that minimize cycle time.

In the study, the Web of Science (WoS), Scopus and Google Scholar databases was searched starting from 2007, when the first study on ALWABP was conducted, and a total of 41 articles were reached. These articles were examined in terms of objective functions, established decision models, additional constraints considered, the solution method applied, the size of the problem solved, the data used in the study, the type of assembly line in which the study was carried out, and the variety of product models. The study carried out is an original study that has not yet been performed in the literature. With this study, it has been provided to shed light on the future studies that can be carried out within the scope of ALWABP and to examine the studies in the literature with a detailed and critical perspective.

The rest of the study are organized as follows. Second part includes the definition of ALWABP, in the third part, the studies carried out within the scope of ALWABP are given. In the fourth section, the findings obtained as a result of the examination are discussed and the data are shared, and finally, in the fifth section, the point reached in the literature on ALWABP is evaluated and the studies that can be carried out in the future periods are emphasized.

## Assembly line worker assignment and balancing problem (ALWABP)

The integer programming model of ALWABP is given in Eqs. 1–7, using the notations given in **Table 1** (6).

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

Subject to

$$\sum_{h\in H}\sum_{s\in S} x_{s_{hi}} = 1, \quad \forall i \in N \tag{2}$$

$$\sum_{s\in S} y_{sh} \le 1, \quad \forall h \in H \tag{3}$$

$$\sum_{h\in H} y_{sh} \le 1, \quad \forall s \in S \tag{4}$$

$$\sum_{h\in H}\sum_{s\in S} s.x_{s_{hi}} \le \sum_{s\in S} s.x_{s_{hj}}, \quad \forall i, j/i \in D_j \tag{5}$$

$$\sum_{i\in N} p_{hi}\ .\ x_{s_{hi}} \le C, \quad \forall h \in H, \quad \forall s \in S \tag{6}$$

$$\begin{aligned} &\sum_{i\in N} x_{s_{hi}} \le M.\ y_{sh}, \quad \forall h \in H, \quad \forall s \in S \\ &M > \sum_{h\in H}\sum_{i\in N} p_{hi} \\ &y_{sh} \in [0, 1], \quad \forall h \in H, \quad \forall s \in S \\ &x_{shi} \in [0, 1], \quad \forall h \in H, \quad \forall s \in S, \quad \forall i \in N \end{aligned} \tag{7}$$

The objective function given in Eq. 1 aims to minimize the cycle time. With the constraint given in Eq. 2, each task $i$ is performed in a single station ($s$) by a single worker ($i$). The constraint given in Eq. 3 provides that each worker $h$ is assigned to at most one station. The constraint given in Eq. 4 ensures that a worker is assigned to each station $s$. The constraint given in Eq. 5, reflects the precedence relationships between tasks $i$ and $j$, where $i$ is predecessor of $j$. It is stated that, with the constraint given in Eq. 6 and the constraint given in Eq. 7, more than one task can be assigned to a worker $h$ assigned to station $s$, provided that the $C$ is not exceeded. Since $C$ and $y_sh$ are decision variables, the constraints given in Eqs. 6, 7 are described respectively to ensure linearity of the mathematical model. Additionally, there are some special constraints in the model for SWDs, which are special environments. These constraints are defined in Eqs. 8–10:

$$\sum_{s \in S} x_{s_{h_i}} = 1, \quad \forall \left(i, h\right) \in A \tag{8}$$

$$y_{s_h} = 1, \quad \forall \left(s, h\right) \in Z \tag{9}$$

$$\sum_{i \in N} \sum_{s \in S} x_{s_{h_i}} \geq 1, \quad \forall h \in H \tag{10}$$

With the constraint given in Eq. 8, it is stated that due to special reasons, some task-worker assignments should be considered as priorities. With the constraint given in Eq. 9, it is ensured that some worker-workstation assignments are considered as a priority owing to the different physical features of disabled workers. With the constraint given in Eq. 10, it is stated that since SWD's philosophy is to bring people with disabilities into business life, all workers must undertake at least one task. This constraint can be applied where the number of tasks exceeds the number of workers available.

Assembly line worker assignment and balancing problem is similar to the second type of problem structure, according to the "classification of ALBP according to objective functions," which has been studied many times in the literature. This problem structure is included in the literature as SALBP-2, which deals with the minimization of the cycle time (1). The ALWAB model mentioned above is called ALWABP-2 (ALWABP-2), which is specifically defined for SWD environments. In this problem, it is aimed to minimize the *C*, taking into account the specific workers and their specific situations. In the classification of ALBP, it is also aimed to determine the appropriate number of workstations for a certain cycle time in the problem category called SALBP-1 (1). In accordance with SALBP-1, ALWABP-1 structure can be formed by establishing ALWAB models. However, the ALWABP-1 structure does not meet the desired objectives for the SWD environment. Because, in the ALWAB model structured for SWD environments, effective use of existing workers and providing more employment are given importance.

**TABLE 1** | Notations related to assembly line worker assignment and balancing problem (ALWAB) problem.

| **i, j** | Task |
|---|---|
| **h** | Worker |
| **s** | Workstation |
| **N** | Set of tasks |
| **H** | Set of available workers |
| **S** | Set of workstations |
| **A** | Set of assignments a priori (*i*, *h*) task-worker |
| **Z** | Set of assignments a priori (*h*, *s*) worker-station and worker-workstation |
| **C** | Cycle time |
| **m** | Number of workstations |
| **phi** | Processing time for task *i* when worker *h* performs it |
| **Dj** | Set of tasks immediately preceding task *j* in the precedence network |
| $x_{s_{h_i}}$ | $\begin{Bmatrix} 1, \textit{Binary variable equal to 1 only if task i is assigned} \\ 0, \textit{other cases} \end{Bmatrix}$ |
| $y_{s_h}$ | $\begin{Bmatrix} 1, \textit{Binary variable equal to 1 only when worker h is assigned to stations} \\ 0, \textit{other cases} \end{Bmatrix}$ |

# Literature review

## Studies on ALWABP

On the basis of ALWABP, it is taken into account that workers are different, they may not be able to perform some tasks, there may be tasks that need to be assigned with priority, or there may be workstations that need to be assigned with priority. Therefore, the ALWABP structure can produce solutions closer to real life. The studies carried out within the scope of this problem structure are given below.

The study performed by (6) is the first study in which ALWABP is shown as a model and defined. In the study, universal design principles were transferred to the working environment and more disabled individuals were brought into working life. A mathematical model was developed by putting forward the assumptions and constraints related to the problem. The developed model has been applied in a firm where electrical components are assembled. The assignment of 7 workers and 18 tasks to 7 workstations was performed with mixed integer programming (MIP). In assignments that have worker-task incompatibilities, task completion times are considered to be infinite.

Chaves et al. (9) searched for solution using Clustering Search (CS) approach to the comparative datasets of four families from small scale to large scale (Roszieg, Heskia, Tonge and Wee-Mag) used in each ALWABP-2 practice and tested it on the relevant benchmark data. The test problem obtained are the data used in future studies. These data, 160 of which are low size and 160 of which are high size, covers 320 problem data (7) advanced the Branch and Bound Algorithm (B&BA) and Heuristic Method (HM) for ALWABP, which provide the solution of small-scale problems. Based on the problem defined by Jackson (4), they solved the problem with B&BA by generating random data.

A two-level, three-factor experimental study was conducted based on the problem defined by Jackson

(4), developed by (10) for the classical SALBP. The original task time was used for the first worker and the task times for the other workers were randomly produced from this. Based on SWD experience, care was taken that the interval taken into account in the randomization of these durations was not more than three times the original task durations. It has been accepted that if a worker cannot complete the task within the specified time interval, this task should not be given to the worker. In order to show this situation in the model, the completion time of the relevant worker is defined as infinite. Within the scope of the study, 1,440 experiments were carried out for 40 problems and 36 different rules.

Chaves et al. (11) used Iterative Local Search (ILS) and CS algorithm together to solve ALWABP-2 test problems. With this hybrid approach they propose, (9) based on highsize data, they reached better results in a shorter time. When the results are examined, the best known solution is found in 314 out of 320 test problem; In 306, the new best solution is found (12) developed a simple, flexible, accurate, and fast Tabu Search (TS) algorithm for ALWABP. Although full priority was not given to accuracy and speed, as is usually the case in the operations research literature, our results show that the method outperforms more sophisticated methods even in these two criteria.

Costa and Miralles (13) implemented a job rotation strategy for ALWABP. The authors suggested the Integer Linear Programming Model (ILPM) and a Heuristic Decomposition Method (HDM) to find a new job rotation problem. The results showed the effectiveness of the proposed heuristic.

Blum et al. (14) introduced an iterative approach based on Beam Search (BS). In the first stage, the algorithm finds the initial *C* for the related problem, and in the second stage, the *C* is reduced until the problem cannot be solved. In the study, 25-28-70-75 staff problems were selected; 32 combinations were created with the factors of number of tasks, number of tasks per worker, task time.

variability, and percentage of task-worker incompatibility. By generating 10 test problems for each of the 32 combinations, a total of 320 test problems were produced, and the best results were found according to the results obtained in the previous studies on the subject in the literature.

Moreira et al. (15) developed Constructive Heuristics (CH) that allow defining priority rules for tasks and tasks that should be assigned to workstations. For the SALBP developed by Scholl and Voß and the CH method, the assignment rules for the station are standardized and these are applied to find the minimum *C* (16). Assignment rules created for each station were applied sequentially, and tasks were assigned to existing stations in a sequence determined according to a priority assignment rule, taking into account the maximum station workload. In the study, task-worker assignment rules were used to determine the tasks and workers that should be assigned to each workstation. Accordingly, 16 task and 3 worker priority rules have been defined. A hybrid solution method has been adopted on the basis of the Genetic Algorithm (GA) based on CH. As a result of the study, when a comparison was made in terms of the studies carried out in this field, the results were obtained as soon as possible.

Zaman et al. (17) adopted the approach of weighting the number of stations with the *C* as the evaluation function in ALWABP. In the study in which test problems were used, GA was applied.

Araujo et al. (18) proposed two new types of the original ALWABP that involve cooperation between different workers. In the first version, the presence of a small number of disabled workers was taken into account, in the second version, results were obtained for assembly lines with workers with different speeds. The authors developed an Integer Programming (IP) model and obtained a solution with CH in order to solve the proposed problem. Here, they applied the two-stage TS approach. In the first stage, a set of tasks that each worker could perform was created; in the second stage, each worker was allowed to choose one set of tasks, provided that each task fell into at least one set of tasks.

Mutlu et al. (19) used an Iterative Genetic Algorithm (IGA), which involves all three of the Modified Bisection Search (MBS), GA, and ILS strategies. They have obtained satisfactory results in short solution times for large-scale test problems.

Moreira and Costa (20) examined the ALBP with heterogeneous workers within the scope of job rotation scheduling. The authors proposed a hybrid algorithm that uses A local search based on MIP neighborhoods (LSMIP-N) to select feasible schedule from solution space of heuristic solutions. The results showed that the proposed method produces fast, flexible, and more precise results compared to existing methods.

Borba and Ritt (21) studied on ALWABP-2. A new MIP model has been proposed for ALWABP, which includes two-index decision variables. In the study, the Probabilistic Beam Search (PBS) algorithm, which finds the best *C* among different *C*, is used by considering the problem type, ALWABP-F, in which the current line's suitability is checked for the conditions where the *C* and the number of stations are known or determined. They hybridized this algorithm with the B&BA procedure. They achieved the best results in almost all of them, except for the Wee-Mag family (the largest of the four problem families in (9)).

Vila and Pereira (22) searched for effective and precise methods that produce solutions for ALWABP-F, taking into account its relationship with SALBP. They developed the BB&RA procedure, which includes three different recall algorithms with and without time constraints of 60 seconds and 600 seconds. As a result of the 600-second time-limited and non-time-limited versions, they obtained the best solutions in the relevant literature.

Ramezanian and Ezzatpanah (23) searched for a solution for the mix-model ALWABP-2 type, which produces more than one product according to the model type on assembly lines. In the problem, it is aimed to minimize the total operating costs incurred for the workers in order to perform the tasks within the total cycle time. Here, the total cycle time is the sum of the *C* corresponding to the maximum processing time for each model at the workstations. For the solution of test problems involving small, medium, and large data, the Imperialist Competitive Algorithm (ICA) was used together with Goal Programming (GP).

Moreira et al. (24) defined the Assembly Line Worker Integration and Balancing Problem (ALWIBP) and proposed a new mathematical model that would enable disabled workers and non-disabled workers to be assigned to tasks together. The authors developed a mathematical model and the Insertion Constructive Heuristic (ICH) for the problem they defined as ALWIBP-1. Thanks to this study, productivity losses were much lower than expected. They also evaluated the performance of the ICH they developed. In this algorithm, the solution obtained by finding a solution for SALBP-1 is adapted to an ALWIBP defined in the study, in which workers with different task completion times are considered.

Moreira et al. (25) proposed the Robust Insertion Constructive Heuristic (RICH), which provides higher solution quality and is faster than B&BA. The aim is to ensure that tasks and employees are assigned to a minimum number of stations. Two models have been developed to enable workers to integrate into assembly lines. RICH has been proposed for these developed models. This heuristic yields high quality solutions within computing times that do not exceed one second for the cases tested. It also identified the best-known solution for some instances.

Castellucci and Costa (Castellucci Costa, 2015) have proposed an approach to hinder real-life congestion or delays at stations for ALWABP. This approach involves the use of a statistical distribution when determining task times. When the task times are shown on the graph, the task times are produced in such a way that a bowl image is formed and used in the ALWAB problem. It has been argued that a more efficient line is obtained with this developed approach. The problem is evaluated using integer task times. In the study using test problems, the Simulation Model (SM) was used. Here, the simulation model is set up for task times.

Araujo et al. (26) presented two heuristic solution methods by establishing a MIP model for the parallel assembly line worker assignment and balancing problem (PALWABP). In the study, in which test problems were used, two algorithms were implemented with one being TS and the other one being Biased Random-Key Genetic Algorithm (BRKGA).

Ritt et al. (27) considered minimization of expected *C* to reflect the uncertainty in cycle times in ALWABP where absenteeism is high. In the study, stochastic worker situation occurs in terms of task time, and for this, a two-stage model has been proposed, considering stochastic worker clusters and their probabilities. An approach is proposed that assigns tasks to the workstation in the first stage and workers to the workstation in the second stage. In the study that uses test problems, solutions were found with Simulated Annealing (SA).

Polat et al. (28) had experimented on the test data for ALWABP using the Variable Neighborhood Search algorithm (VNS). In the first of the proposed two-stage approach to minimize the cycle time, the VNS approach is performed to assign tasks to workstations; In the second stage, the variable neighborhood descent algorithm was used to assign the workers to the workstations. This developed approach has been tested with previously used benchmark data. Also, the proposed algorithm has been applied in an electronic company producing LCD TVs. When the results are examined, it is observed that the algorithm gives effective and robustness results.

Zacharia and Nearchou (29) focused on the ALWABP, which deals with the minimization of the smoothness index of the *C* and the workload of the line. In the study, the Multi-Objective Evolutionary Algorithm (MOEA), which has never been used in the literature before, was applied as a solution approach.

Moreira et al. (30) presented the multi-objective ALWIBP-2. The problem is aimed at minimizing *C* and maximizing the integration of heterogeneous workers while maintaining productivity levels. In the study, Miltenburg smoothness index, which is frequently used in just in time production, was used to determine the productivity level. The authors formulated the model and proposed the Worker Regularity Constructive Heuristic (WRCH) for the solution.

Oksuz et al. (2017) aimed to maximize the line efficiency by considering the worker performance for the U-type ALWABP. First, they formulated a nonlinear model of the problem and then linearized it. The proposed model was used for line balancing and worker assignment objectives in a tractor production assembly line and small-scale test problems. In addition, Artificial Bee Colony Algorithm (ABCA) and GA were used for the solution.

Pereira (31) proposed ALWABP based on the interval data. In the study, in which the lower and upper limits of the terms of office are included, it is aimed minimizing the absolute maximum regret between whole possible scenarios. The problem is solved using exact and heuristic solution methods.

Efe et al. (32) examined the ALWABP with workers of different ages and genders for minimizing the number of stations. While assigning the workers to the stations, their physical workload capacity and, accordingly, the time to complete the tasks were considered. Workers were evaluated in six different age classes in order to make age analysis. Binary Linear Programming (0-1)(BLP) is recommended for ALWABP, in which the physical workload capacity varying according to gender and age are evaluated. The effectiveness of the proposed model has been demonstrated in test problems and real-life applications for a textile company. ALWABP was solved by considering the task times of an assembly line with 53 tasks in a textile company and the physical workloads of the workers.

Yılmaz and Demir (33) have developed a new model that provides effective results in task assignments without exceeding the *C*. In the study, readily available test problems were used. Since the lack of mathematical model is observed, the authors introduce a new mathematical formulation with objective function to minimize the cycle time for ALWABP. As a result of the experiments, it is observed that the proposed mathematical model is very effective in terms of solution quality and CPU time than the current mathematical method.

Akyol and Baykasoğlu (34) have proposed a constructive heuristic approach for ALWABP. They studied on the Multiple-Rule Based Constructive Randomized Search (MRBCRS) by describing priority rules for 39 tasks and 4 workers for the ALWABP-2 solution. Efficiency of the suggested MRBCRS is compared with the related literature on benchmark instance. Experimental results obtained show that the proposed MRBCRS is very effective for benchmark problems. When the results are examined, considering the methods developed in the literature so far, it shows that the solution has improved in terms of quality and time.

Akyol et al. (34) discussed Ergo-ALWABP by adding ergonomic risk factors to the approaches proposed by (34) in their study. In addition to the cycle time criterion in the structure of the problem, the necessity of balancing the workload between stations has been emphasized in the studies. In the traditional approach, since it is thought that two workers in two different stations with the same station times have equal workloads, an approach that is far from real life is exhibited. Therefore, an ALWABP problem has been introduced that considering ergonomic risk factors (ErgoALWABP). The proposed problem is handled with a MRBCRS. Besides, Occupational Repetitive Action (OCRA) method is implemented for assessment of ergonomic risk. Efficiency of the advanced method is compared with the related literature on benchmark innstance. The results obtained show that the production environment can be improved ergonomically with this approach, which is evaluated with ergonomic risk factors.

Shin et al. (35) addressed a problem involving parallel assembly line and tasks with the need of multiple workers for ALWABP-2. In addition to ALWALP, the model has been developed to allow simultaneous workstation parallelization and assignment to tasks that require multiple workers. They compared both the solution obtained with the mathematical model and the solution obtained by the heuristic method they developed.

Liu et al. (36) discussed the uncertainty in the matter of worker absence in the ALWABP. Here, the uncertainty created by the changing workforce is reflected in the model. In the study, an objective function, which takes into account the weighted sums of the *C* obtained for the scenarios established and the penalties due to insufficient number of workers, is discussed. The developed model is used in a small-scale problem with 8 and 10 tasks.

Liu et al. (37) provided the inclusion of the risk that may occur due to the uncertainty in the times in the objective function for assembly lines where the task times are not known. This study is in the form of risk averse model to solve ALWABP under uncertain trading time by incorporating a risk measurement method called conditional Value at Risk (CVaR). In the study, the objective function was created as the minimization of the *C*. First, the risk-averse scenario-based ALWABP is by commercial solver to find how CVaR impacts the objective value. Then, in order to better inflect the random nature, for this problem, Instead of capturing only a certain objective value obtained with a small sample, the SAA (Sample Average Approximate) approach is adopted to obtain a statistical lower bound information. In a small-scale problem, the developed model is tested.

Janardhanan et al. (38) discussed the ALBWAP, which deals with two-sided assembly lines. In the study, the best solution was found for small-scale problems, and a solution was sought for large-scale problems by using Migrating Birds Optimization (MBO). The solutions produced by the proposed algorithms are compared with other familiar metaheuristic algorithms such as ABCA and SA. Comparision analysis shows that the suggested method can prosper optimal solutions for small-scale problems and more effective results are obtained than benchmark algorithms for large-scale problems.

Zacharia and Nearchou (39), in addition to their work in 2016, also examined the problem in a fuzzy environment, taking into account the uncertainty in task time. Here, minimizing simultaneously the line's fuzzy cycle time and the fuzzy smoothness index is aimed. In this study, the fuzziness of data is represented by Triangular Fuzzy Numbers (TFNs) In the study using test data, a solution was obtained with the Fuzzy Multiobjective Genetic Algorithm (FMGA).

Zhang et al. (40) solved the ALWABP for U-type lines. In the study, walking times were neglected while performing the tasks. All workers can perform any task with different task times. With the U-type line in question being a line where only one product is produced, the priority relations of the tasks are known. Each task is assumed to be performed by exhibiting a working posture (movement of a worker's upper limbs). The model built with these assumptions is solved by minimizing the *C* and the total ergonomic risk at all workstations. In the study, the test data was used by applying the mathematical model. In the study, Restarted Iterated Pareto Greedy Algorithm (RIPGA) was used for large scale problems.

Topaloğlu Yıldız et al. (41) proposed a two-stage approach to solving the problem of balancing assembly lines by assigning workers to workstations. In the first stage, a mathematical model was developed by taking into account the proficiency status of the jobs, the presence of workers at the time of assignment, the equipment required for the jobs and their positions at the workstations. The task and worker assignment results obtained as a result of the solution of the mathematical model were used to evaluate whether the desired production targets could be achieved in real life. Here, factors such as conveyor activity between workstations, intermediate inventory areas and stochastic variability in processing times, which cannot be regarded in the mathematical model, are also included in the evaluation process using the ARENA SM. The model was evaluated using data from the production line of an electronics company that assembles the back cover. Since it is observed that the results obtained after the two stage approach do not reflect the desired target, a solution reaching the production target is obtained by proposing improvement strategies regarding the existing system.

Yılmaz (42) aimed to reflect the different setup times that occur in assembly lines, including the disabled, to the production flow and to increase production efficiency. Accordingly, in the study, a structure was created in which setup times for ALWABP-2 were included and MIP and SA were applied.

Liu et al. (43) developed a risk averse model that minimizes both the total cycle time and the number of temporary workers employed, based on the assumption that rates of not being able to continue working may be high for individuals with disabilities. In the study, uncertainty was tried to be managed by establishing a stochastic model. This developed model has been tested on small-scale problems and solved with GA combining both MIP and K-means Clustering Approach (KMCA) and VNS algorithm. In addition to the fuzzy definition of *C* and smoothness index in their study in 2020.

Liu et al. (44) has addressed the problem of assigning multi-skilled workers and balancing the assembly line, which takes into account energy consumption, since labor assignment and energy consumption have an important place in terms of production performance. In addition to assigning workers to workstations at certain cycle times, the study also includes scheduling of products. It includes two objectives: total costs, including the cost of processing and the fixed cost of hiring workers and energy consumption. A bi-objective mathematical model is proposed and an *e*-constraint method is integrated with achieve the Pareto front for small-scale problems. To find solution for large-size problems, a processing time and energy consumption sorted-first rule (PT-EC SFR), a multi-objective genetic algorithm (NSGA-II) and a multi-objective simulated annealing method (MOSA) are advanced. The results reveal that among the proposed solution approaches, PT-EC SFR is better in terms of computation time and quality of solution.

Zacharia and Nearchou (45) argued that there is a tradeoff between *C* and smoothness index and that pareto solutions can be obtained. It first demonstrates how fuzzy concepts can be applied to the management of ambiguous task times. The solution to the issue is then put forth using a multi-objective genetic algorithm (MOGA). Finding Pareto-optimal solutions is the purpose of MOGA. Two distinct MO approaches—a weighted-sum based approach and a Pareto based approach—are built and tested within MOGA to facilitate efficient trade-off decision-making. In the study, results were obtained by using FMGA for test problems.

Katiraee et al. (46) developed a mathematical model for the ALWABP that performs appropriate worker assignment based on the worker's experience and physical demand. These characteristics, which vary from worker to worker in the study, form the Worker-Task Categorization Matrix (WTCM). With the data obtained here, the "Borg score" was computed, which allows the employee to be appointed considering the ergonomic conditions. According to the method, if the score is higher than 4; it indicates that the task requires high experience and physical demand, and it should be ensured that assignments are made accordingly. In the problem where the *C* and maximum physical workload are minimized, the maximum physical workload that is not expected to be exceeded is defined as an additional constraint. Since there are two objectives, Pareto Optimum Solution (POS) are obtained in the problem defined with two objectives.

Çimen et al. (47) discussed the Rebalancing the assembly line and the issue with employee task involving ergonomic components defined as Ergo-ALWABP. In the developed model, there are 7 different objectives. The primary objective is to reduce the overall cost of rebalancing, which includes costs such as opening or closing workstations or moving tasks, additional equipments or workers, additional rentals or inventory. In the second objective, minimizing the average similarity factor between the initial assembly line and the rebalanced assembly line are considered. The third objective is to maximize the average similarity factor between the initial assembly line and the rebalanced assembly line, which ensures that the similar workers are assigned in terms of tasks. The fourth objective is to minimize the ergonomic risks for which the Occupational Repetitive Action Index (OCRA) is used. In the fifth objective, minimizing the number of tasks carried in rebalancing is focused. The sixth objective is to maximize line efficiency based on production time, workstation and *C* and the seventh objective is to minimize the smoothness index. In addition to assembly line rebalancing constraints, the model uses a constraint that ensures that the average OCRA index is determined and not exceeded. This problem, which was presented for the first time, was tried in test problems and solved with MRBCRS.

The studies carried out within the scope of the ALWABP mentioned above are evaluated in the **Tables 2–4** within the scope of the objective function, decision model, additional constraints considered, the solution method used, the size of the problem solved and the data used.

**TABLE 2 |** Evaluation of studies on ALWABP different dimensions in the literature between 2007 and 2012.

| References | Objective function | Decision model | Assembly line according to the station layout | By model variety | Additional constraints, if exists | Solution method | Problem data used |
|---|---|---|---|---|---|---|---|
| Miralles et al. (6) | Minimization of cycle time | Yes | Straight line | Single product | ALBWAP constraints were created for the first time. | IP | 7 workers, 18 tasks, 7 workstations |
| Chaves et al. (11) | Minimization of cycle time | No | Straight line | Single product | None | CS | Test roblems |
| Miralles et al. (7) | Minimization of cycle time | Yes | Straight line | Single product | Constraint of assigning a task to each worker in cases where the number of tasks exceeds the number of workers. | B&BA, HM | Randomly generated. |
| Chaves et al. (9) | Minimization of cycle time | No | Straight line | Single product | None | ILS, CS | Test problems |
| Moreira and Costa (12) | Minimization of cycle time | Yes | Straight line | Single product | None | TS | Test problems |
| Costa and Miralles (13) | Maximizing different tasks performed by workers | Yes | Straight line | Single product | Constraint for not to exceed the average cycle time due to rotation | MIP, HDM | Test problems |
| Blum ve Miralles (14) | Minimization of cycle time | Yes | Straight line | Single product | Constraint for assigning a lower limit to the cycle time | BS | Test problems |
| Moreira (15) | Minimization of cycle time | Yes | Straight line | Single product | Constraint that ensures no assignment due to duty-worker mismatch | CH | Test problems |
| Zaman et al. (17) | Minimizing cycle time and idle time and maximizing efficiency | No | Straight line | Single product | None | GA | Test problems |
| Araujo et al. (18) | Minimization of cycle time | Yes | Parallel line | Single product | Additional constraints on parallel line concurrent execution and collaborate | MIP, CH, TS | Test problems |

As can be seen in **Tables 2–4**, the studies carried out until 2012 were performed for straight assembly lines. Although the same is generally true for future studies, there are also studies on U-type assembly lines (Oksuz et al., 2017, 48), parallel assembly lines (18, 35). In addition, studies carried out within the scope of independent parallel assembly lines (Borba and ve Ritt, (21)) and two-sided assembly lines (Janardhanan et al., (38)) have also been seen in the literature. In terms of product model variety, the only two studies that consider the mixed model assembly line are those of (23, 44).

When **Tables 2–4** are examined, it is seen that the minimization of the *C* is included in the objective function of most studies. Only a few studies have ever used this objective function (17, 20–23, 29–Oksuz et al., 2017, 48). In addition to that, (23) minimized *C* and operating costs; (29, 39, 45), evaluated the minimization of *C* and smoothness index simultaneously.

As a similar two objectives, Liu et al. (37, 44), using the probability values regarding the simultaneous cycle time and the case of temporary workers being assigned due to worker absenteeism, expressed two aims of minimization (32), on the other hand, aimed to minimize the number of stations, depending on whether the station was opened or not.

Assembly line worker assignment and balancing problem is a problem that is difficult to solve. It is almost impossible to get a solution in the desired time frame for large-scale problems. When the studies in **Tables 2–4** are examined, each study except (6), which defined ALWABP, used metaheuristic methods. Although (18, 26), Moreira et al. (24, 27) used MIP for ALWABP, they also used heuristic methods because of the fact that MIP would be insufficient in solving large-scale problems. The most commonly used heuristic methods are the GA, B&BA, BS, and CH approaches. Other heuristic methods are TS, VNS, EA, MBO, ABCA, and ICA as seen in **Tables 2–4**. In addition, it is seen that the SM is used for solving this problem, although it is limited. While this method is used by Castellucci and Costa (Castellucci Costa, 2015) to obtain bowl solutions in terms of task times, it is used by Yıldız et al. (2020) to include real-life factors such as conveyor movements, inventory area, and worker and task assignment by simulation method.

Miralles et al. (7), Borba and ve Ritt (21, 22), and Borba et al., (2014) used B&BA in their studies (7) proposed heuristic-based B&BA with different parameters. Among the three different strategies, Depth First Search (DFS) gave the best results. Borba and ve Ritt (21)

**TABLE 3 |** Evaluation of studies on ALWABP different dimensions in the literature between 2013 and 2017.

| References | Objective function | Decision model | According to the station layout | By model variety | Additional constraints, if exists | Solution method | Problem data used |
|---|---|---|---|---|---|---|---|
| Moreira and Costa (20) | Maximizing the number of tasks assigned to workers | Yes | Straight line | Single product | Constraint to provide job rotation | LSMIP-N | Test problems |
| Mutlu et al. (19) | Minimization of cycle time | No | Straight line | Single product | None | IGA | Test problems |
| Khemyong and Sirovetnukul (48) | Minimizing the number of stations and walking time and maximizing the station's full-time operation | Yes | U line | Single product | Constraints that will allow assignment to the U-type line | MIP | Real application on garment factory |
| Vilà and Pereira (22) | Assignment control based on different cycle time and number of stations | No | Straight line | Single product | None | BB&RA | Test problems |
| Borba and ve Ritt (21) | Minimization of cycle time and assignment control based on different cycle time and number of stations | Yes | Straight line | Single product | New two-index task and worker assignment constraint | B&BA, PBS | Test problems |
| Araujo et al. (26) | Minimization of cycle time | Yes | Parallel line | Single product | A constraint to enable parallel operation | MIP, TS, BRKGA | Test problems |
| Ramezanian and Ezzatpanah (23) | Minimization of cycle time and processing cost | Yes | Straight line | Mixed model | Constraint based on worker skill levels | GP, ICA | Test problems |
| Castellucci and Costa (Castellucci Costa, 2015) | Minimization of cycle time | Yes | Straight line | Single product | The constraint that ensures the balanced distribution of task times | SM | Test problems |
| Moreira et al. (24) | Minimizing the number of stations | Yes | Straight Line | Single product | Hierarchical worker assignment constraint | MIP, ICH | Test problems |
| Moreira et al. (25) | Minimizing the number of stations | Yes | Straight line | Single product | Hierarchical worker assignment constraint | MIP, RICH | Test problems |
| Ritt et al. (27) | Minimization of expected cycle time | Yes | Straight line | Single product | A new constraint in which the uncertainty in cycle times caused by worker absenteeism is stochastically limited over cycle time | MIP, SA | Test problems |
| Zacharia and Nearchou (29) | Minimization of cycle time and smoothness ındex | No | Straight line | Single product | None | MOEA | Test problems |
| Polat et al. (28) | Minimization of cycle time | Yes | Straight line | Single product | Constraint specifying tasks that should be assigned priority to workstations due to certain equipment and region restrictions | MIP, VRS | Test problem and real life application |
| Öksüz et al. (2017) | Minimization of cycle time and number of stations (MHDï¿ ¡ A-E) | Yes | U Line | Single Product | None | MIP, ABCA, GA | Test problems and real application |
| Moreira et al. (30) | Minimization of cycle time and maximization of worker integration | Yes | Straight line | Single product | Constraint Of Miltenburg Smoothness Index | MIP, WRCH | Test problems |

and Borba et al. (2014) proposed B&BA with new task-oriented rules that set lower bounds (22) suggested a B&BA with station oriented rules based on the BB&R rule. The results from these studies revealed that the proposed approaches give the best solution for large-scale test problems.

## Conclusion

In this study, the studies carried out until today for the ALWABP, put forward by Miralles et al. (6), are considered. In each study, the differences are explained, and the solution methods that are differentiated are transferred with respect

**TABLE 4 |** Evaluation of studies on ALWABP different dimensions in the literature between 2018 and 2022.

| References | Objective function | Decision model | According to the station layout | By model variety | Additional constraints, if exists | Solution method | Problem data used |
|---|---|---|---|---|---|---|---|
| Pereira (31) | Minimizing the maximum regret based on task times | Yes | Straight line | Single product | A constraint that ensures that the task time stays between the lower and upper limits | MIP, HM | Test problems |
| Efe et al. (32) | Minimizing the number of stations | Yes | Straight line | Single product | Constraint limiting physical workload | BLP | Test problems and real application |
| Yılmaz and ve Demir (33) | Minimization of cycle time | Yes | Straight line | Single product | New two-index task and worker assignment constraint | MIP | Test problems |
| Akyol et al. (34) | Minimization of cycle time | No | Straight line | Single product | None | MRBCRS | Test problems |
| Akyol et al. (34) | Minimization of cycle time and Risk Factor | No | Straight line | Single product | None | MRBCRS | Test problems |
| Shin et al. (35) | Minimization of Cycle Time | Yes | Parallel line | Single product | Additional constraint for parallel lines and multiple workers on the line | MIP, HM | Test problems |
| Liu et al. (36) | Minimization of penalties due to stochastic weighted cycle time and insufficient number of workers | Yes | Straight line | Single product | Constraints in which workforce uncertainty is evaluated stochastically | MIP | Problem with 8 and 10 task |
| Liu et al. (37) | Minimization of cycle time | Yes | Straight line | Single product | Constraints defining the risk of uncertainty in task times | MIP, SAA | Test problems |
| Janardhanan et al. (38) | Minimization of cycle time | Yes | Two sided assembly line | Single product | New worker and task assignment constraints for two-sided assembly line design | MIP, MBO | Test problems |
| Zacharia and Nearchou (39) | Minimization of cycle time and smoothness index | Yes | Straight line | Single Product | Fuzzy task time constraint | FMGA | Test problems |
| Zhang et al. (40) | Minimization of cycle time and overall ergonomic risks across all workstations | Yes | Straight line | Single product | Constraint limiting ergonomic risks caused by repetitive tasks | RIPGA | Small scale problem with 9 task |
| Yıldız et al. (2020) | Minimize cycle time with the least number of workers | Yes | Straight line | Single product | Constraints that include the proficiency of workers on the job, absences of workers, and the workstation locations of the equipment used | MIP, SM | Electronic company application with 41 tasks and 19 workstations |
| Yılmaz (2020) | Minimization of cycle time | Yes | Straight line | Single product | Constraint on task start times, taking into account task preparation times | MIP, SA | Test problems |
| Zacharia and Nearchou (39) | Minimization of Cycle Time and Smoothness Index | Yes | Straight line | Single product | Task times are added into the constraint in a fuzzy way | FMGA | Test problems |
| Liu et al. (43) | Minimization of risk from weighted sums of cycle time and temporary workers | Yes | Straight line | Single product | Stochastic constraint involving the use of temporary workers | MIP, GA | Test problems with 20 and 30 task |
| Liu et al. (44) | Minimization of the total costs and energy consumption | Yes | Straight line | Mix product | Constraints to ensure product scheduling, total cost and energy consumption | NSGA-II, MOSA | Test problems |
| Katiraee et al. (46) | Minimization of cycle time and maximum physical workload | Yes | Straight line | Single product | Constraint limiting physical workload | POS | Real application |
| Çimen et al. (47) | Minimize rebalancing cost, average similarity ratio, ergonomic risks, number of tasks carried in rebalancing and smoothness index, maximize average similarity ratio for workers, line efficiency | Yes | Straight line | Single product | Constraint limiting ergonomic risks caused by repetitive tasks | MRBCRS | Test problems, real application |

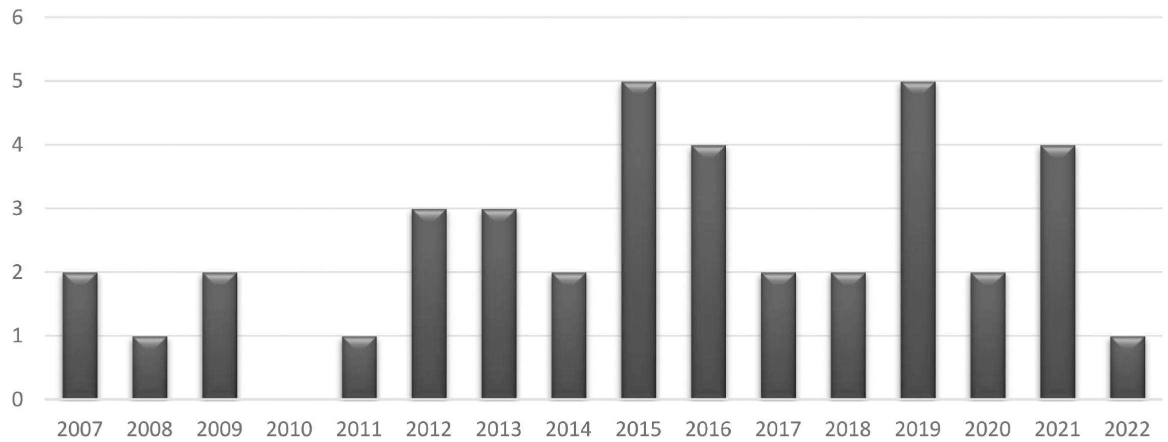


**FIGURE 1 |** Number of studies according to years.

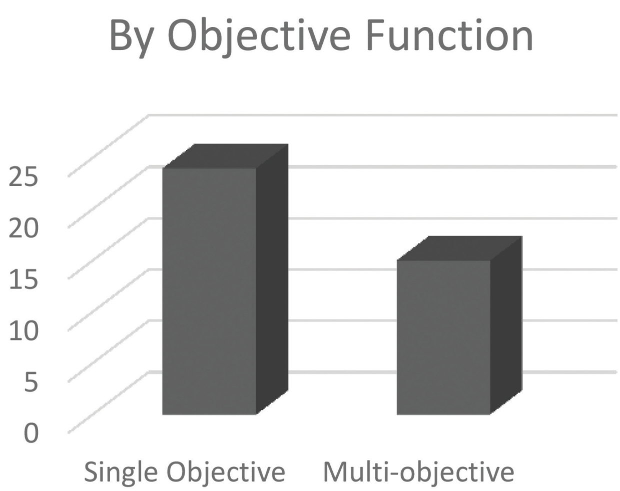


**FIGURE 2 |** Distribution of studies examined according to objective functions.

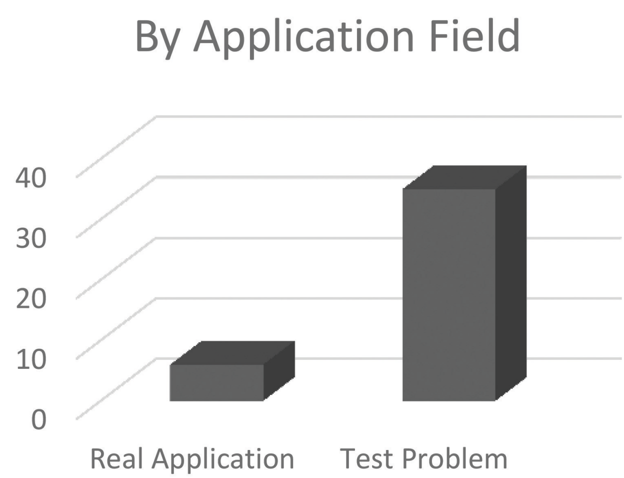


**FIGURE 4 |** Distribution of studies on the use of test problems or the real application.

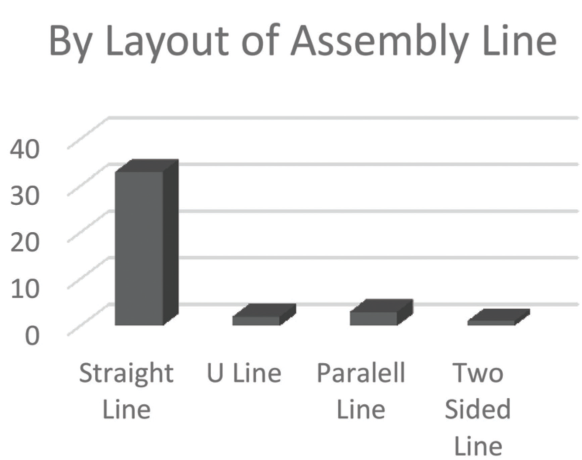


**FIGURE 3 |** Distribution of studies according to the solution method used.

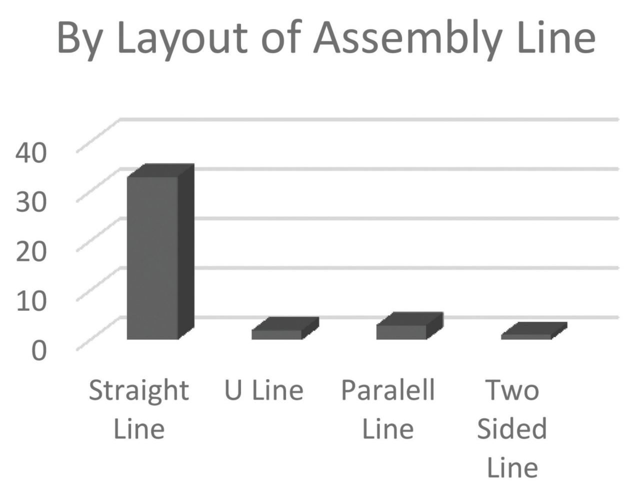


**FIGURE 5 |** Distribution of studies by assembly line layout.

to the first study carried out by (6). In **Figure 1**, the number of studies published by years; in **Figure 2**, the distribution of studies according to whether they are single-objective or multi-objective; in **Figure 3**, the distribution of solution methods used in the studies; in **Figure 4**, the distribution of the studies according to whether they contain real applications or use test data; in **Figure 5**, the distribution of the studies according to the types of assembly lines on

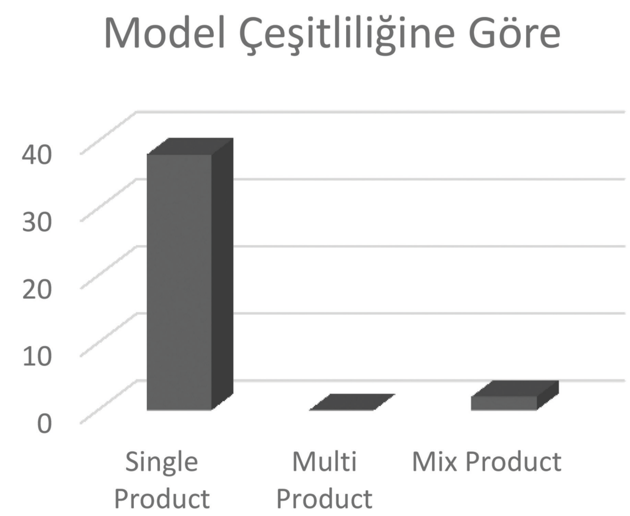


**FIGURE 6 |** Distribution of studies by assembly line model diversity.

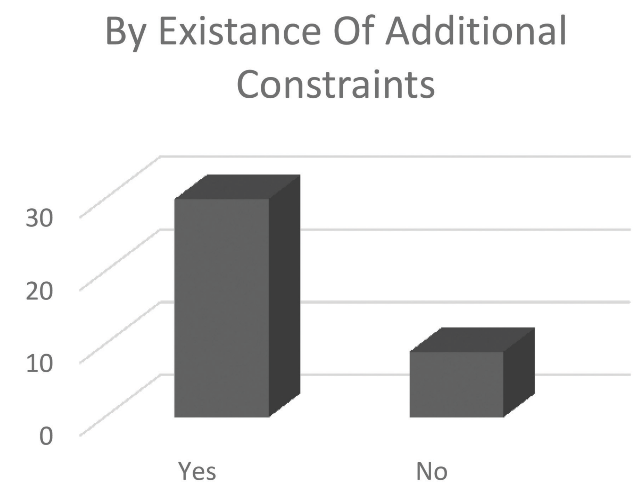


**FIGURE 8 |** Distribution of studies whether there are additional constraints in the models.

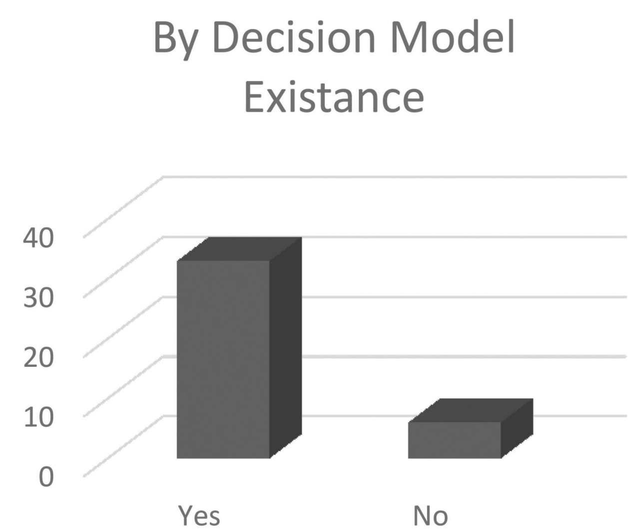


**FIGURE 7 |** Distribution of studies by decision model existence.

which they are carried out; in Figure 6, the distribution of the studies according to the lines that produce single-product or multi-product; in Figure 7, the distribution of the studies according to whether they contain a decision model or not; and in Figure 8, whether there are additional constraints in the models established in the studies are given.

When Figure 1 is examined, it has been determined that the most studies were conducted in 2015 and 2019, respectively.

When Figure 2 is examined, it has been determined that the studies are generally carried out for a single objective. When Figure 3 is evaluated, it is seen that heuristic approaches are generally used as a solution method in studies. According to Figure 4, it was determined that test problems were generally used in studies. In Figure 5, it was revealed that the studies were generally carried out for straight lines. According to Figure 6, it was determined that single product lines were preferred in the studies. When Figure 7 is evaluated, the existence of decision models has been determined in most of the studies. When looking at Figure 8, it is seen that additional constraints are mostly added to the model.

## Discussion

It is of great importance for industrial enterprises in terms of balancing assembly lines, increasing production speed, and making effective production plans, taking into account heterogeneous worker characteristics and differences in production conditions depending on these characteristics. Accordingly, it becomes easier to design production in the most efficient way and to keep it flexible enough to respond to changes under increasing competition and difficult market conditions. When the literature is examined, it is seen that most of the studies have remained at the theoretical level, and very few studies have been performed in practice. Although there are many reasons for this, one of the main reasons is the neglect of worker differences that arise in practice. ALWABP, which was defined by Miralles (6) and is based on the idea that workers are different from each other, performs a balancing act dependent on the worker performing the task on the assembly line. In this problem structure, workers may not be able to perform the task, they may not be assigned to that task, or they may perform that task very slowly. In ALWABP, there is an assignment and balancing based on compatibility for the task.

In the study, a literature search was carried out, which included the applications made within the scope of ALWABP from the day it was defined until today. Con sidering that 2022 is not over, it has been determined that interest in ALWABP has started to increase again as of 2021. When the studies for ALWABP are examined, the most striking point is that the studies are carried out on the lines where a single model is produced. Except for a few studies, the solution method has been proposed instead of model development. In addition to that, the idea of minimizing the completion time of the workers has been advocated in the studies carried out until today, starting from the study conducted by Miralles (6). Only a few studies have performed assignment and balancing for other purposes. In addition, it has been observed that there are few studies in which the real application is made and evaluations are made on the developed test problems. As a solution approach, the use of heuristic approaches draws attention. When the studies in the literature were evaluated, it was determined that ergonomic factors were considered in a limited number of studies, and it was determined that this point should be given importance in terms of production efficiency. Evaluation by integrating ergonomic factors into the model as much as possible will ensure that the results obtained converge more with real life. Ergonomics aims to increase performance by arranging the work organization in accordance with the physical and psychological characteristics of the worker so that workers can perform their tasks efficiently and by improving the conditions for ensuring worker health and work safety. In this sense, the working environment conditions (noise exposure, required lighting level, exposure to vibration, etc.) and the harmony of the worker's anthropometric characteristics with the working area play an important role in the worker's production efficiency. By transferring these elements to ALWABP, it will be possible to design and balance assembly lines with more accuracy and precise analysis.

## Author contributions

Both authors contributed to the study conceptualization and design, data collection, analysis and result interpretation, and manuscript preparation.

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