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Review

Research Trends and Outlooks in Assembly Line Balancing Problems

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Abstract. This paper presents the findings from the survey of articles published on the assembly line balancing problems (ALBPs) during 2014-2018. Before proceeding a comprehensive literature review, the ineffectiveness of the previous ALBP classification structures is discussed and a new classification scheme based on the layout configurations of assembly lines is subsequently proposed. The research trend in each layout of assembly lines is highlighted through the graphical presentations. The challenges in the ALBPs are also pinpointed as a technical guideline for future research works.

Keywords: Assembly line, line balancing, ALBP research trends, layout based classification.

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1. Introduction

An assembly line is a form of production processes in which some workstations lined up serially are interconnected with one another by a transport mechanism (called a paced line), e.g. conveyor, robot, etc. The assembly process starts with feeding necessary raw materials to the first workstation at a constant rate. After that, in each workstation, a predefined set of tasks (i.e. smallest undividable elements of work) are carried out to sequentially put together assembly parts on the main structure of the product according to the instruction given by the assembly process chart. The semi-finished product remains in the workstation for an interval equal to the cycle time (i.e. available time for an operator to work on the product) and then it is moved to the next workstation along the line to perform another set of tasks. At the end of the line, after completing all the necessary operations, a finished good is produced. On the other hand, in an un-paced line, no transport equipment is available, and workers control the movement of workpieces between workstations by building up queues between workstations and alter their working speed to satisfy customer demands or their personnel desires.

The assembly line balancing problems (ALBPs) involve the assignment of tasks to a set of workstations placed in a sequential order such that all the predefined tasks are executed, no precedence relation (i.e. sequence which tasks must be performed to realise a finished product) is violated, and the work content (total task time) of the workstation is not greater than the cycle time, to optimise some specific objective. The first analytical model on the ALBPs was formulated by Salveson [1]. Since then, the ALBP was the topic that has received great attention from research scholars when considering the number of articles published [2]. The ALBPs are categorised in an NP-hard class of combinatorial optimisation problems since their simplest version is known as a bin packing problem. The number of possible task sequences is $m!/2^r$ for the problem with m tasks and r preference constraints which is enormous for large-sized problems. Unsurprisingly, voluminous efficient algorithms have been developed to obtain optimal or near-optimal solutions for the ALBPs [3].

A well-known classification scheme for the ALBPs was proposed by Baybars [4], i.e. simple assembly line balancing problem (SALBP) and general assembly line balancing problem (GALBP). The key assumptions of the SALBP comprise the followings, i.e. the layout of the line is serial (straight line), a single product is assembled on the paced line, all tasks are allowed to perform at any workstation, all workstations are capable of doing any task, and all input parameters are deterministic. For the remaining problems using the assumptions other than these, they are named as the GALBP. Moreover, within both groups of problems, the ALBPs could be categorised further as follows. Type I minimises the number of workstations for specified cycle time. In contrast, given the number of workstations, the cycle time is minimised in Type II. Type E attempts to maximise line efficiency by adjusting the number of workstations and cycle time. If the objective of the ALBPs is to find a feasible solution for a given number of workstation and cycle time, it is labelled as Type F.

Such a classification scheme of the SALBP and GALBP seems inappropriate with nowadays' research progress. The research on the SALBP is in the maturity stage since effective problem-solving tools and techniques have already been developed for many decades. Contrarily, in the later, more and more effort has been paid to extend the GALBP to reflect real-world industrial problems, especially by integrating a variety of practical constraints and characteristics in a collective manner. This introduces a great non-homogeneity within the voluminous publications of the GALBP. A few notable classification schemes have also been proposed recently, e.g. Boysen et al. [5], Battaïa and Dolgui [6]. However, their classification schemes were too comprehensive to young researchers and practitioners to follow because diverse contexts of the ALBPs were brought together in the review, e.g. disassembly, machining, etc. Besides, reviewing the ALBPs through attributes and constraints may lead to confusion and causing difficulty in referring back and forth since some of them are common while others are limited to only particular layouts.

In the early days of the evolution of assembly lines, the main layout was a straight line or a little bit more advanced beyond that might be a U-shaped line (U-line). At that time, the concept of the U-line was just emerged to support the JIT production and still not well-known in the industry. Therefore, it is unsurprising that such classification of the ALBP using SALBP and GALBP was enough to differentiate distinct characteristics between both groups when conducting literature surveys [4]. However, presently, the number of articles on the SALBP starts to be saturated; whereas the GALBP's articles are increasing considerably as a result of the development of new layout styles, e.g. parallel assembly lines (PAL), two-sided assembly line (2SAL), etc. These layouts have distinctive appearances, attributes and characteristics which could be easy to comprehended and exploited in categorising the research groups. Therefore, to make the literature review to be more effective and able to articulate the review to reflect the cutting edge of the research in each group appropriately, we propose to broadly structure them according to their layout configurations.

The benefits derived from the division of literature based on their layouts are as follows. First, it enables readers to realize that they are now focusing on which type of layout. Each layout has its specific characteristics and constraints which are different from others; therefore, the review could be more focused by in-depth elaborating on the knowledge domain relevant to the associated layout. Second, the academic advancement in each layout may not be the same. The literature review with referencing to the layout would clearly articulate such progress and stage. Third, research benchmarking among different layouts could be easily conducted to identify a research gap and the newly-formed layout could gain benefits from knowledge transfer from the research results from long-established layouts.

The objective of this article is to give a comprehensive review of the most recent trends, between 2014 and 2018, in the ALBP research concerning various existing layout configurations. Based on this framework, the similarities and dissimilarities among published literature are discussed and the outlook for the future is provided. The remaining contents presented in this paper are organised as follows. In section 2, the new classification scheme in reviewing the ALBPs is proposed. Sections 3 – 9 provide literature reviews on the ALBP based on their different layout configurations. Findings from literature reviews are summarised in Section 10. In Section 11, the trends and perspectives on the ALBP are discussed. Finally, Section 12 dedicates to the concluding remarks of the survey.

2. Proposed Classification Scheme

Several classification schemes have been proposed to facilitate the review of the ALBP research. The guideline that seems more prominent than others was probably the SALBP and GALBP proposed by Baybars [4]. However, such classification guideline is not suitable for current research trends since almost all recent publications are more engaged in GALBP's variances. The key characteristic used to broadly divide the ALBP's body of knowledge domain into groups should be something that is a highlight of the research and easily identified by sight (i.e. appear in the article's title and keywords) which is the layouts of the assembly lines. Therefore, in this paper, the types of layouts consist of the straight-shaped assembly line (StAL), U-shaped assembly line (U-line), assembly line with parallel workstations (PWAL), two-sided assembly line (2SAL), parallel assembly lines (PAL), multi-manned assembly line (MAL) and hybrid line (HL). The HL is constructed from the combination of two or more basic layouts (e.g. parallel U-line (PUAL), parallel two-sided (P2SAL) and two-sided U-line (2SUAL). The types of layouts could reflect the characteristics of workstations, tasks, constraints and the manner how they are operated. Once the broad domain of the ALBP (i.e. layout) is identified, the following attributes of the assembly line are used to address specific problem areas.

- Number of models: The number of product models assembled in the line can be single (the line produces only one model), multi-model (more than one product models are assembled in batch), and mixed-model (more than one product models are assembled in an arbitrarily intermixed manner).
- Variation of task time: Task time can be considered as fixed and deterministic (reliable machines/tools and skilled workers perform only simple and standardised tasks), stochastic (effectiveness of workers is unknown when balancing the line; hence, the task time follows some distribution function due to motivation, fatigue, work environment, defect or unpredicted machine/tool breakdown), and dynamic (variation caused by learning effect, experience or deterioration effect of workers).
- Type of problems: Different types of problems are conventionally optimised in the ALBP including Type I, Type II, Type E and Type F as mentioned earlier. Also, Type Cost is considered more often to represent a cost-related ALBP which aims to optimise some objective functions such as assignment cost, equipment purchasing cost, inventory cost, resource (machine) cost, workforce cost, etc. The remaining types of problems are classified in Type O (others) which could include the problems that attempt to optimise smoothness index, energy consumption, etc.
- Number of objectives: The number of objectives to be optimised in the ALBP can be single and multiple objectives. For the single objective optimisation problem, the objective to be optimised will be corresponding to the type of problems, e.g. ALBP Type I attempts to minimise the number of workstations given the cycle time. In some problems, more than one objective function is optimised simultaneously. For example, multi-objective ALBP Type I must optimise the number of workstations plus additional objectives such as minimise workload distribution among workstations. Nevertheless, the type of problems is still indicated by the primary objective to be tackled.
- Solution techniques: In this category, three types of solution techniques are used, i.e. (1) exact solution ((E) a mathematical approach used to solve an optimisation problem to give an analytical solution, e.g. linear programming, dynamic programming, etc.), heuristic ((H) problem-solving algorithm using a practical method, e.g. rule of thumb, intuitive judgement, etc.) and metaheuristic ((MH) a higher-level heuristic designed to find, generate, or select a partial search procedure that could result in an acceptably good solution to an optimisation problem, e.g. genetic algorithm, particle swarm optimisation, etc).
- Task assignment control: The limitation in assigning a set of tasks to workstations is stated in the zoning control. If a set of tasks is mandatory to assign to the same workstation, it is called positive zoning. On the other hand, negative zoning prohibits certain tasks to be assigned to the same workstation. The positional constraint allows the assignment of some tasks to some specific positions in the workstation only. Moreover, if the execution of two or more related tasks on different workstations has to be done in parallel, it is called the synchronous constraint.
- Other special factors: There may be some factors other than those mentioned previously that could influence the way to assign tasks to workstations. These factors are normally specifically occurred in

some specific cases to extend the conventional ALBPs to be more resemble real industry cases. These factors are skills, learning effect, ergonomics, etc.

- Simultaneous decision: To gain a holistic view of the assembly system, the ALBPs could be jointly optimised along with some other decision problems, e.g. sequencing, buffer allocation, etc. Such concurrent decision making could lead to a new challenge in the research of the ALBP.
- Real industry case: The application of the ALBP to the real case study is also observed in this paper. This number demonstrates the success rate that theoretical knowledge can bridge the gap in industrial practices.

Figure 1 shows the proposed classification scheme of the ALBP used in the review of the articles in this paper. The row under the ALBP is the layouts of the assembly lines and below that are the attributes of the problems.

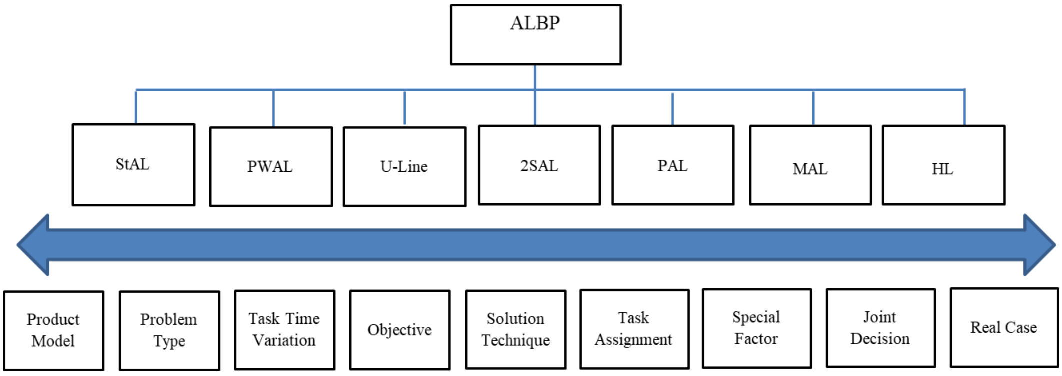


Fig. 1. The structure of the classification scheme in the ALBP.

3. Straight-Shaped Assembly Line

A straight-shaped assembly line (StAL) is the traditional assembly line in which some workstations are arranged sequentially. Parts are assembled in sequence on the semi-finished product and move from one workstation to another until the whole assembly operations are completed. The StAL is normally utilised to take benefits of economies of scale in mass production to achieve high system efficiency and low per-unit cost of products. Otto and Otto [7] studied the application of priority rule-based methods (PRBMs) which exploited knowledge gained from the specific problem to generate good solutions within a short time for the StALBP. To alleviate the issue of slow warm-up period of exact or metaheuristic solution methods, PRBMs were recommended as their initial solution generators. Saif et al. [8] studied the optimisation of the mixed-model assembly line balancing and sequencing problems simultaneously. The objectives for the ALBP were to balance the workload for different models in each station and to reduce the deviation of workload on a station from the average workload of all the stations. Meanwhile, the objective of the sequencing problem was to minimise the total flowtime of different models. A multi-objective artificial bee colony (multi-ABC) was proposed to find the Pareto optimal solutions. Al-Hawari et al. [9] studied a multiple assignment (forward, backward, and bidirectional) method with the GA (MA-GA) for the SALBP to minimise the actual number of workstations, maximize the line efficiency and minimize the workload variation. Sungur and Yavuz [10] studied worker assignment by considering levels of workers to assign workers and tasks to the stations to minimise total cost. Integer linear programming (ILP) was formulated to solve assembly line balancing with hierarchical worker assignment (ALBHW) problem. Buyukozkan et al. [11] studied the mixed-model straight assembly line balancing problem (StALBP) to optimise the lexicographic bottleneck objective which was the hierarchical minimisation of the weighted workload from the heaviest to the lightest workstations, one by one. The artificial bee colony (ABC) and Tabu search (TS) algorithms were proposed as solution methods. Alavidoost et al. [12] formulated a bi-objective mixed-integer fuzzy linear programming model (BOFMILP) for the StALBP with the uncertain environment to minimise the number of station and the cycle time. A two-phase interactive fuzzy programming is used as a solution method. Pınarbaşı et al. [13] formulated an integrated model of the queuing network (QN) and constraint programming (CP) to minimise the smoothness index (SI) value in stochastic assembly lines. Alavidoost et al. [14] applied a modified GA employing one-fifth success rule in operator chosen to optimise the efficiency and idleness percentage of the line and also minimise the number of workstations. The triangular fuzzy numbers were used to represent the variation in the processing time of tasks. Nilakantan et al. [15] proposed an integer programming (IP) model to minimise the total production cost for a robotic assembly line balancing problem. The differential evolution (DE) algorithm was employed to minimise the cycle time and total assembly line cost simultaneously. Akpinar et al. [16] adopted an algorithm based on the benders decomposition (BDA) technique to minimise the number of workstations in the case where setup times depended on the sequence of tasks allocated to workstations in a mixed-model assembly line. Li and Boucher [17] addressed the automated line balancing problem with task learning and dynamic task reassignment in automated flexible assembly systems. The backward induction rules (BIR) were developed to rebalance the line and reduce the number of workstations. Kim et al. [18] proposed three mathematical models, i.e. integer linear programming (ILP) and mixed-integer linear programming (MILP) for a mixed-model StALBP with unskilled temporary workers to minimise the total cost of labour and workstation cost, minimise the maximum cycle time and minimise the total work overload, respectively. A genetic algorithm (HGA) hybridised with a heuristic algorithm was developed for the cost-oriented objective. Fathi et al. [19] compared twenty constructive heuristics to minimise the number of workstations in the StALBP Type I. Besides, the smoothness index was not recommended to use as the fitness function in optimising the problem. Bukchin and Raviv [20] applied the constraint programming (CP) model to solve the StALBP Type I, Type II and other variants, i.e. task assignment and equipment selection problems. The CP model showed better performances than the MILP and SALOME branch-and-bound methods for small and large problem instances. Li et al. [21] studied the robotic ALBP to minimise the cycle time. Four mixed-integer linear programming models and two meta-heuristics, i.e. simulated annealing (SA) and restarted simulated annealing (RSA), were proposed to solve small and large problems, respectively. Li et al. [22] studied the simultaneous balancing and sequencing problems of the robotic mixed-model assembly line. A mixed-integer linear programming model was developed for small-sized problems. For large-sized problems, the RSA and the restarted co-evolutionary genetic algorithm (RCoGA) were proposed. Nilakantan et al. [23] applied two metaheuristics, i.e. particle swarm optimisation (PSO) and differential evolution (DE) to solve the robotic assembly line balancing (RALB) problem. The efficient set of robots was selected to perform the tasks in the assembly line and the efficiency of its usage was optimised in the line effectively. Salehi et al. [24] formulated a multi-objective mixed-integer linear programming (MILP) model for the ALBP with fuzzy parameters. Three objectives were optimised simultaneously, i.e. minimising the number of stations, minimising the total cost of labour and equipment and minimising the total disqualification rate. A hybrid fuzzy interactive (HFI) approach comprising two phases was proposed, i.e. (Phase I) to find an equivalent crisp model based on credibility measure, and (Phase II) to apply an interactive fuzzy programming method to find Pareto optimal solutions. Yuan et al. [25] discussed that the reconfigurable ALBP for cloud manufacturing environment comprised two optimisation phases, i.e. (early phase) assembly line planning and (later phase) assembly line operations. The objectives to be optimised in the early and later phases comprised minimising the number of workstations given the cycle time and minimising the smoothness index given the cycle time and the number of workstations, respectively. A memetic algorithm (MA) was proposed to solve the problem. Azizoğlu and Imat [26] formulate a mixed-integer linear programming (MILP) model for a simple ALBP to optimise the workload smoothness, given the number of workstations and cycle time. A branch-and-bound (B&B) was developed to find optimal solutions for medium-sized instances. Ritt and Costa [27] proposed an improved formulation of the precedence constraints and the station limits used in the integer programming (IP) model in the SALBP. It was revealed that more optimal solutions and best values were discovered. Borba et al. [28] proposed a MILP model, a branch-bound-and-remember (BBR) method and an interactive beam search (IBS) with problem-specific dominance rules to solve the robotic ALBP of Type II. Pereira et al. [29] studied the cost-oriented robotic ALBP in which tasks and robots were assigned to workstations simultaneously to minimise the installation (fixed) and operations (variable) costs. The genetic algorithm (GA) with a memetic algorithm (MA) as a local search was proposed as a solution procedure. Pereira [30] presented MILP models to minimise the weighted sum of costs related to the allocations of heterogeneity labour and machinery to workstations. The Hoffmann heuristic combined with an estimated of distribution algorithm (EDA) was applied to solve the problem. Pereira [31] considered the worker assignment and assembly line balancing problem in which task times depended on the skills of workers to achieve robust solutions (i.e. favourable for all possible scenarios). The interval data min-max regret (IDMR) framework was used such that task times were assumed uncertain but restricted to take values within an interval. Mixed-integer linear programming and a heuristic were proposed as solution methods. Pereira and Álvarez-Miranda [32] considered the Bertsimas-Sim (B&S) robust form of the SALBP in which operation times were uncertain but their values could be taken from specific intervals, namely rSALBP-I. The branch, bound and remember (BBR) technique was formulated to solve the problem. Dong et al. [33] proposed a bi-objective chance-constraint MILP model for the SALBP in which the equipment costs varied according to a negative linear function of task times. A particle swarm optimisation (PSO) with the SA as a local search (PSO/SA) was proposed to find the Pareto front of the equipment cost and the cycle time. Huo et al. [34] developed an ant colony optimisation (ACO) model hybrid with a beam search algorithm (ACO-BS) to solve the SALBP. Mardani-Fard et al. [35] studied the stochastic ALBP where task times and dis-quality levels of tasks followed normal distributions. Three objectives were optimized including the average quality performance of workers, equipment purchasing cost and worker time-dependent wage. A hybrid between fuzzy programming (FP) and goal programming (GP) methods was proposed. Babazadeh et al. [36] studied the stochastic ALBP in which task times were uncertain and represented by triangular fuzzy numbers. A multi-objective genetic algorithm (MOGA) based fuzzy programming (FP), as well as the enhanced non-dominated sorting genetic algorithm II (NSGA-II), was proposed to optimise two objectives, i.e. minimising the number of workstations and the fuzzy cycle time. Lai et al. [37] considered the ALBP Type E. They developed the stability radius of an optimal line balance (STABRAD) algorithm to find an optimal line balance and then analysed the optimal line balance to reduce the number of re-balancing times. Zhang [38] proposed an immune genetic algorithm (IGA) to solve SALBP Type I to minimize the number of workstations and the smooth index. Leitold et al. [39] considered the SALBP Type II in which task times were stochastic. According to the empirical task-time distributions concept, the sum of the stochastic production lines was computed from the convolution of the empirical density distribution functions of the working times. Empirical Working time distribution-based line balancing with Simulated annealing and Dynamic programming (EWSD) method which was a two-phase optimisation algorithm used a SA to generate feasible task sequences and then applied dynamic programming (DP) to optimally assign tasks to workstations, was proposed. Efe and Kurt [40] applied the interval type-2 trapezoidal fuzzy (IT2TrF) numbers with the technique for order preference by similarity to ideal solution (TOPSIS) method to minimise the number of stations under the physical workload and maximise total of closeness coefficient of each person assigned to the assembly line. Zhou and Wu [41] formulated a mathematical model for a robotic weld ALBP in which changeover times of fixtures were considered to minimise the cycle time. An adaptive GA with the SA mechanism (ASAGA) was proposed to solve the problem. Foroughi and Gökçen [42] applied a chance-constrained programming model for the ALBP with stochastic task times to minimise the total cost of one unit. A multiple rule-based GA was developed for large-sized problems. Table 1 summarises the survey of the StAL.

4. Parallel Workstation Assembly Line

A parallel workstation assembly line (PWAL) is normally configured as a StAL in which some of its workstations are duplicated and worked in parallel. The PWAL is useful to increase the flexibility of the system in terms of adaptability to changes in demands and handling machine failures. Moreover, the cycle time of parallel workstations can be shorter than the largest task time resulting in the productivity improvement on the bottleneck workstation without adding another line. Öztürk et al. [43] simultaneously studied the line balancing and cyclic scheduling problems of flexible assembly lines with parallel workstations that produced mixed-model products to minimise the cycle time. The problem was solved by constraint programming (CP). The knowledge specific search strategy with symmetry breaking constraints was exploited to increase search efficiency. Tiacci [44] simultaneously considered two interrelated problems, i.e. mixed-model assembly line balancing problem with parallel workstations and buffer allocation problem, to minimise the normalised design cost. The genetic algorithm (GA) embedded with the parametric simulator was the proposed solution technique using to determine the impacts of tasks and buffer allocation decisions. Rabbani et al. [45] studied mixed-model assembly line balancing problem of type I with parallel workstations. Two objectives were considered, i.e. minimise the number of workstations and maximise workload smoothness between workstations. The non-dominated sorting genetic algorithm (NSGA II) and multi-objective particle swarm optimisation (MOPSO) were employed as solution techniques. Table 2 shows the summarisation of the survey on the PWAL.

5. U-Shaped Assembly Line

A U-shaped assembly line (U-line) has been adopted to replace a StAL in many industries to realise the benefits of just-in-time production. The U-line is always divided into three parts, i.e. Front, Back and Bottom, where workstations are accommodated along with a narrow U. Workers enter the line at the Front leg and after completing all required operations they exit at the Back leg of the line. Besides, workers could perform tasks on either leg (regular workstations) or both legs (crossover workstations) of the line. Fattahi and Turkay [46] demonstrated that the precedence constraints normally used in the mixed-integer linear programming (MILP) formulation of the U-line to minimise the total assignment cost in some papers caused infeasible optimal solutions. The revised version that accurately formulated the either-or precedence constraints was proposed without adding new constraints or variables in the model. Alavidoost et al. [12] formulated a bi-objective mixed-integer fuzzy linear programming model (BOFMILP) with the uncertain environment to minimise the number of station and the cycle time. A two-phase interactive fuzzy programming is used as a solution method. Li et al. [47] formulated an integer programming (IP) model to solve the U-line balancing problem of Type II. A heuristic-based on multiple rules, i.e. task selection, task assignment and task exchange rules, was proposed as a solution technique. Oksuz et al. [48] considered the Type E problem of U-line in which assembly operations were performed manually by workers. Because different skills of workers, actual task times depended on who performed the tasks. Therefore, the performance coefficient of each task per each worker was utilised to refer to the worker's skill. A non-linear mathematical model was proposed for simultaneously solving the worker assignment and balancing problem. An artificial bee colony (ABC) and a genetic algorithm (GA) were developed for large-sized problems. Li et al. [49] applied a branch, bound and remember (BBR) algorithm to minimise the number of workstations for the U-line balancing problem. To improve the performance of the conventional BBR algorithm, several methods were developed, e.g. modified Hoffman heuristic, dominance rules, the method to renumber the tasks, the criterion to select a sub-problem and method to reduce the number of sub-problems. Fathi et al. [19] illustrated that the smoothness index was not suitable for using as the fitness function to solve the UALBP Type I. Among twenty constructive heuristics, the greatest processing time divided by the upper bound and the longest processing time heuristics were the best ones for minimising the number of workstations. Meanwhile, the greatest average rank positional weight and the smallest task number performed best for the smoothness index. Wang et al. [50] proposed a mixed nonlinear integer linear programming (MNILP) model for the mixed-model UALBP Type II to optimise weighted objectives, i.e. cycle time, workload balancing of each workstation and the average value of the standard deviation of the operation time. Learning effect and stochastic operation were considered in the model. GA was used as a solution method. Babazadeh et al. [36] optimised two conflicting objectives simultaneously, i.e. minimise the number of workstations and minimised the fuzzy cycle time. Triangular fuzzy numbers were used to deal with uncertainty and vagueness of the cycle time and task times in the fuzzy linear programming (FLP) model. An enhanced non-dominated sorting genetic algorithm (enhanced NSGA II) was proposed to solve the problem. Nejad et al. [51] proposed an algorithm based on grouping evolutionary strategy (GES) to solve the UALBP Type I. The approach used revised ranked positional weight to generate an initial solution, three selection mechanisms to generate new solutions, and the COMSOAL and critical path methods to boost the performance of the algorithm. Zhang et al. [52] incorporated machine deteriorate and preventive maintenance into the UALBP. The problem was solved in two stages, i.e. (1) normal U-line balancing, and (2) reassign tasks to workstations when some machines were unavailable due to maintenances. NSGA II and multi-objective simulated annealing (MOSA) were employed to optimise cycle time and task assignment alterations simultaneously. Zhang et al. [53] considered the worker assignment and UALBP concurrently. The iterated greedy algorithm (IG) was proposed to solve the problem. Many heuristics were used to create diversified initial solutions and the solutions were improved by destruction and construction methods and local searches. An enhanced migrating birds optimisation (EMBO) algorithm was also proposed for Type II of their previous problem [54]. Zhang et al. [55] jointly addressed the U-line balancing and energy consumption reduction problems in a robotic assembly line. A non-linear multi-objective mixed-integer non-linear programming (NMMIP) model was proposed. A Pareto artificial bee colony (PABC) algorithm was proposed to optimise large-scale problems. Table 3 summarises the research works on the U-line.

6. Two-Sided Assembly Line

A two-sided assembly line (2SAL) consists of double-sided directly-facing assembly workstations arranged on a single assembly line to perform different tasks on the same product in parallel. Unlike straight lines (one-sided lines), in 2SALs, both sides of the lines (left and right sides) are utilised simultaneously to produce high-volume large-sized standardised products such as cars, buses, trucks, heavy machinery, engines and shovel-loaders. The operation direction constraint of the 2SAL restricts some tasks to be assigned on a particular side only; meanwhile, others can be assigned on any one side of the line. Jawahar et al. [56] addressed a two-sided assembly line balancing problem (2SALBP) to optimise two objectives, i.e. minimising the number of workstations, minimising the unbalance time among workstations. Two algorithms were proposed to evolve the Pareto optimal front, i.e. enumerative heuristic (EHA) and simulated annealing (SA) algorithms. Tuncel and Aydin [57] considered a 2SAL in an international company that produce home appliances. Several real-life constraints were taken these constraints into account including workstation related, positive and negative zoning and synchronisation constraints. Teaching-learning based optimisation algorithm was proposed to minimise the number of workstations and balance workload among workstations. Wang et al. [58] considered a 2SAL of an engineering machinery company in which such constraints as the number of operators at each workstation, positional, zoning and synchronous task constraints were enforced. An imperialist competitive algorithm (ICA) embedded with the late acceptance hill-climbing (LAHC) algorithm were used to optimise the line length and the number of workstations. Purnomo and Wee [59] studied a 2SAL with zoning constraints. A mathematical model was formulated to minimise the cycle time and maximise line efficiency. A harmony search (HS) algorithm was proposed to solve the problem. Aghajani et al. [60] formulated a mixed-integer programming (MIP) model for a robotic mixed-model 2SALBP which considered the task assignment and robot allocation to workstations to minimise the cycle time. Simulated annealing (SA) was used as a solution technique for large-sized problems. Yuan et al. [61] proposed an integer programming (IP) for 2SALBP with zoning, positional and synchronism constraints. A late acceptance hill-climbing (LAHC) algorithm was developed to solve large-sized problems. Yuan et al. [62] proposed a honey bee mating optimisation (HBMO) hybridised with SA which was acted as workers to improve broods to minimise the number of mated-stations and minimise the number of stations for mixed-model 2SAL. Lei and Guo [63] consider the Type II problem of 2SALBP. A variable neighbourhood search (VNS) algorithm was proposed, besides the side selection and precedence-based operators were used to create new solutions. Chiang et al. [64] considered the 2SALBP with stochastic task times, i.e. normally distributed with known means and variances. A particle swarm optimisation (PSO) algorithm was proposed to minimise the line length and number of stations. Sepahi and Naini [65] studied 2SALBP in a locomotive production plant where the performance of the task on one side of the line was influenced by the parallel task on the other side (i.e. parallel performance of tasks). A mixed-integer programming model was formulated and the problem was solved by a heuristic. Tang et al. [66] considered the type II problem to minimise the cycle time and the total weighted overload and under-load. The discrete artificial bee colony (DABC) enhanced with blending idle time reduction technique was proposed. Yang et al. [67] proposed a multi-neighbourhood based relinking algorithm (MN-PR) in which a path relinking operator and infeasible solution fixing strategy was integrated into the algorithm to minimise the number of mated-stations and stations. Li et al. [68] formulated a mathematical program for multi-objective 2SALBP Type E. The objectives included maximising the line efficiency, minimise the smoothness index and minimise the total relevant costs per product unit. A multi-objective improved teaching-learning based optimisation (MITLBO) algorithm was proposed to find an optimal Pareto set. Li et al. [69] considered the robotic 2SALBP Type II to minimise the cycle time. A mixed-integer programming model was developed and the problem was solved by a co-evolutionary particle swarm optimization (C-PSO) algorithm. Li et al. [70] considered the 2SALBP in which robots performed operations. The objectives of this study were to minimise the energy consumption of robots and minimise the cycle time simultaneously. A mixed-integer programming model was formulated and a restarted simulated annealing (RSA) was proposed to find an optimal Pareto front. Li et al. [71] formulated the Type II problem of the 2SALBP with positive and negative zoning using an integer programming model. An iterated greedy (IG) algorithm embedded with a local search that considered precedence relationships and modified neighbourhood based heuristic (NEH) were developed for large-sized problems. Li et al. [72] presented two new decoding methods and tested on meta-heuristics. To gain further improvement on the solutions, graded objectives were proposed. The iterated greedy (IG) algorithm was modified to solve the 2SALBP Type I. Delice et al. [73] presented a modified particle swarm optimisation (PSO) with negative knowledge in which new procedures of generation and decoding were developed to solve the mixed-model 2SALBP. Two objectives were considered, i.e. minimising the number of mated stations and minimising the number of stations. Tang et al. [74] presented a mathematical model for the stochastic 2SALBP which taken this into account the positional, zoning and synchronism constraints to minimise the number of mated stations and the number of stations. A hybrid algorithm between the teaching-learning based optimisation (TLBO) and variable neighbourhood search was proposed for the problem. Hu and Wu [75] illustrated that the smoothness index (SI) and mean absolute deviation (MAD) were not suitable for measuring the workload balance among workstations in the 2SAL. Hence, the finish-time-based SI (FSI) and mad (FMAD) was proposed instead. A heuristic integrated with finish time-based MAD was developed to smoothening workloads among workstations. Duan et al. [76] proposed an improved artificial bee colony (IABC) algorithm embedded with the MaxTF and random rules for the 2SALBP Type II to minimise the cycle time. Li and Coit [77] tested several priority rules on the 2SALBP to minimise the number of positions. The priority rules-based methods (PRBMs) was incorporated into the bounded dynamic programming (BDP) named the PR_BDP algorithm was proposed. Li et al. [78] proposed a co-evolutionary cuckoo search (CoCS) algorithm which was the combination of the discrete cuckoo search (DCS) and co-evolutionary (Co) algorithms to solve the task assignment and robot allocation simultaneously. Li et al. [79] developed a multi-objective hybrid imperialist competitive algorithm (MOHICA) with late acceptance hill-climbing (LAHC) algorithm as a local search method to solve mixed-model 2SALBPs with zoning, synchronous and positional constraints. The objectives were to minimise the combination of the weighted line efficiency, weighted smoothness index and the weighted total relevant costs per unit of a product. Kucukkoc et al. [80] formulated a mathematical model for mixed-model 2SALBP with underground workstations. An ant colony optimisation (ACO) algorithm was used to optimise two objectives, i.e. minimise the number of stations and minimise the number of mated stations. A summarised research on the 2SAL is shown in Table 4.

7. Multi-Manned Assembly Line

A multi-manned assembly line (MAL) is a kind of production line that a group of workers concurrently is assigned to perform a set of tasks on the same individual product in multi-manned workstations to make positive collaboration on related different tasks among the workers to realise the outcome. The MAL is suitable for the production of large products, e.g. truck, bus and automobile. Kellegöz and Toklu [81] formulated an integer programming (IP) model for small-size MAL problems. The constructive heuristic (COH) and GA-based improvement procedure (GASA) was proposed for large-size instances. Kellegöz [82] proposed a mixed-integer programming (MIP) formulation to optimised two objectives prioritised as minimising the number of workers first and then minimising the number of workstations second. A simulated annealing (SA) algorithm working on Gantt representations of problem solutions was developed for large-size problems. Roshani and Nezami [83] formulated a mixed-integer programming (MIP) model for a mixed-model multi-manned ALBP to optimise two objectives prioritised as minimising the number of workers first and then minimising the number of workstations second. Simulated annealing (SA) algorithm was developed to solve medium- and large-scale problems. Roshani and Giglio [84] developed a mixed-integer programming (MIP) model for a single-model multi-manned ALP Type II. Two objectives were optimised in a priority of minimising the cycle time first and a total number of workers second. To solve medium- and large-scale problems, two SA heuristics namely direct simulated annealing (DSA) and indirect simulated annealing (ISA) were proposed. Naderi et al. [85] considered a realistic automotive assembly line with specific requirements, i.e. five-sided workpieces, moving multi-manned workers and restricted workspace. The problem was formulated by a mixed-integer programming (MIP) model enhanced with a tighter linear relaxation to effectively decrease solution space and number of iterations. Alghazi and Kurz [86] studied mixed-model multi-manned assembly line balancing considered the zoning, task assignment and ergonomic constraints to minimise the number of workers. The problem was formulated as integer programming (IP) and constraint programming (CP) models. They revealed that the constraint programming model outperformed the integer programming model for large-sized problems. Chen et al. [87] proposed a mixed-integer programming (MIP) model for multi-manned ALBP with resource constraints (e.g. specialised machinery, tools and skilled operators) to minimise the number of workstations, operators and resources. A hybrid heuristic (HH) approach which combined the GA and the procedure to determine feasible balancing solutions were employed as a solution. Table 5 is the summarisation of the survey in the MAL.

8. Parallel Assembly Lines

Parallel assembly lines (PALs) are an extension of the straight line where more than one line located in parallel producing the same or different products works collaboratively through common workstations (i.e. the merging of the neighbouring workstations on adjacent lines, so-called multi-line station) to achieve a better balance of the overall system, high efficiency and increase productivity. Hemig et al. [88] proposed a dynamic programming approach to tackle an integrated problem of production and staff planning in an automotive plant where the final assembly shop was equipped with heterogeneous PAL. The problem was formulated as a nonlinear mixed-integer programme (NMIP). Dynamic programming was used to minimise the cost of the production plan to realise forecasted demand. Rabbani et al. [89] considered mixed-model PALs operated under the policy of assemble-to-order where similar products were produced on both lines, but the speed of one line (express line) was faster than the other. A hybrid GA (HGA) was developed to minimise the weighted stochastic cycle time. Rabbani et al. [90] considered the mixed-model PAL with stochastic task times where task duration followed a uniform distribution to minimise the number of workstations. The SALBP was converted to the resource-constrained project scheduling problem and then applied the particle swarm optimisation algorithm (PSO) as a solution technique. Özcan [91] considered the environment of the PAL in a stochastic task time framework where random events could disturb the assembly system. The constrained, piecewise-linear, mixed integer programming (CPMIP) and Tabu search (TS) were developed to optimised Type I problem. The summary of the research on the PALs is shown in Table 6.

9. Hybrid Assembly Line

To gain the synergy advantages from one or more individual layouts and promote the production of flexible model variation, more balance workload between workstations and higher labour productivity, the hybridisation of standard assembly layouts have been proposed in the literature. These hybrid assembly lines (HAL) include parallel U-lines (PUALs), parallel two-sided assembly lines (P2SALs), and two-sided U assembly line (2SUAL). The review of each layout is given as follows.

Parallel U-lines

The PUALs was firstly presented by Kucukkoc and Zhang [92]. This layout was designed to take advantages of two standard configurations, i.e. U-line and parallel lines. The salient feature of this layout was that workers were allowed to work on multi-line workstations which were placed between two adjacent U-lines located in parallel to each other. Two heuristics based on ranked positional weight method and a maximum number of immediate successors were proposed to find balancing solutions.

Parallel two-sided assembly lines

The P2SALs configure with two or more two-sided assembly lines located in parallel to one another working collaboratively. Workers could be assigned to perform their tasks on left or right side of the line (i.e. mated stations) as normal two-sided assembly lines or in the middle of the adjacent two-sided assembly lines (multi-line) to work on both lines to minimise their idle times. Kucukkoc and Zhang [93] proposed an agent-based ant colony optimisation (ABACO/S) to solve mixed-model parallel two-sided assembly lines balancing and sequencing simultaneously to minimise the number of workstations. Kucukkoc and Zhang [94] formulated integer linear programming (IP) to minimise weighted objectives of idle times of the stations, workload smoothness and line length for their previous problem [93] and again the problem was tackled by ABACO/S. Kucukkoc and Zhang [95] formulated an integer programming (IP) model for the P2SAL balancing problem aiming at minimising the number of workstations by maximising the sum of the square of workload on each workstation and the problem was solved by the genetic algorithm (GA). The problem of Type E was also formulated using integer linear programming to minimise cycle time and number of workstations [96]. The ant colony based (ACO) algorithm was used to solve the problem. The mixed-model version of Kucukkoc and Zhang [95] was solved by flexible agent-based ant colony optimisation (ACO) to minimised weighted sum of line length and the number of workstations [96]. Ağpak and Zolfaghari [97] proposed a mixed integer programming (MIP) model to solve the extended versions of the problem, i.e. Type II problem, cost-oriented model, time and space constraints and assignment restrictions. Tapkan et al. [98] formulated a mathematical programming model for a parallel two-sided assembly line in which walking times were taken into account in the model. The bee algorithm (BA) and artificial bee colony (ABC) algorithm were proposed as a solution method.

Two-sided U-line

The 2SUAL is structured as a U-line in which both sides of the lines are utilized in parallel and workers are allowed to work at either side (left or right) of the line (i.e. mated stations) or in the centre of the U-line (i.e. crossover stations). Delice et al. [99] proposed a solution approach which based on the GA and priority-rule based heuristic to solve stochastic 2SUAL balancing problem to minimise the number of positions (i.e. line length) as a primary objective and minimise the number of workstations as a secondary objective. Delice et al. [100] considered the deterministic version of the problem and proposed the PSO with the task selection and X matrix updating procedures to optimise the number of stations and positions for given cycle time.

The summary of the surveys on the PUALs, P2SALs and 2SUAL are shown in Table 7.

10. Findings from the Survey

The literature in the area of the ALBP published during 2014-2018 was analysed in this section. Ninety-nine (98) papers were issued in the last five years indicating that the ALBP still maintains its movement momentum in the body of knowledge. Having reviewed the collection of the ALBP literature, ten interesting findings are synthesised and worth detailed discussing, i.e. number of published papers versus years, types of problems, number of objectives, solution techniques, number of product models, operational constraint of the task, characteristic of task time, real case problem and simultaneous decision problem. The followings are the findings observed from reviewing the papers.

Number of published papers versus years

Figure 2 shows the total number of papers published in each layout plotted versus years. From 2014 to 2018, the number of published papers was 11, 12, 17, 14 and 44, respectively. The average yearly publications were about 20 papers and 98 papers were published in total. Out of 98 papers, 13 papers dealt with the robotic assembly line. Moreover, the upward trend was observed in the number of publications.

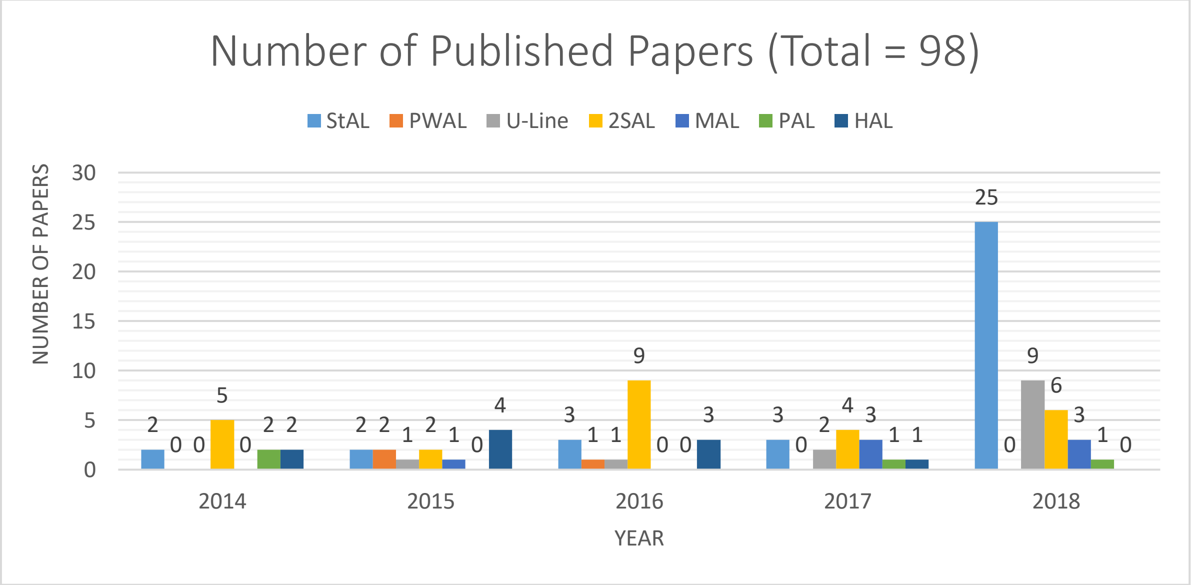


Fig. 2. The number of published papers on the ALBPs during 2014-2018.

From Fig. 3, the top three layouts having most research outputs were the StAL (36%), 2SAL (27%) and U-line (13%). Meanwhile, the number of papers published in the PWAL was the lowest (3%). When considering the publication rates from different types of layouts, it is observed that the StAL and U-line had upward trends (Figs. 4(a)-(b)). In contrast, the publications of PUAL and 2SUAL had stopped since 2015 and 2018, respectively (Figs. 4(c)-(d)).

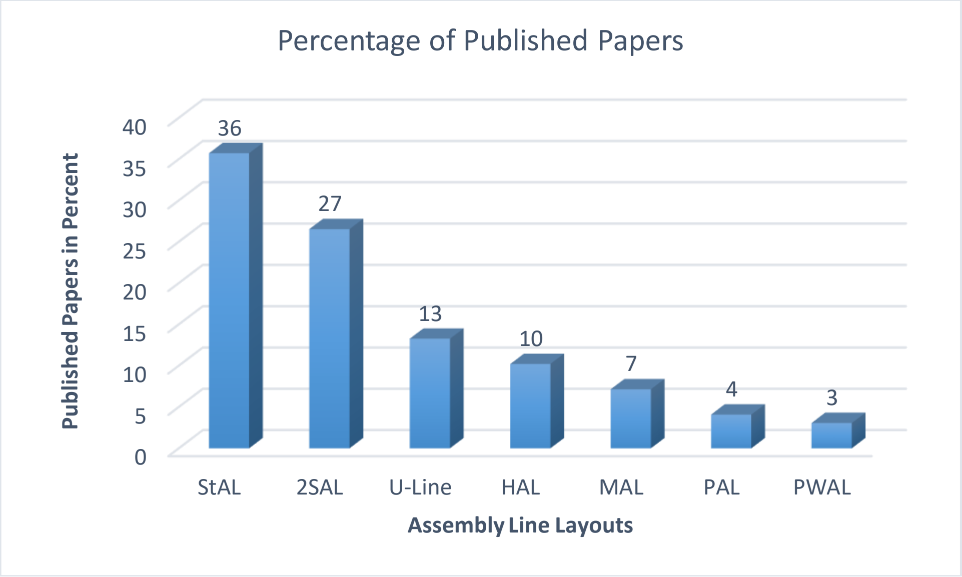
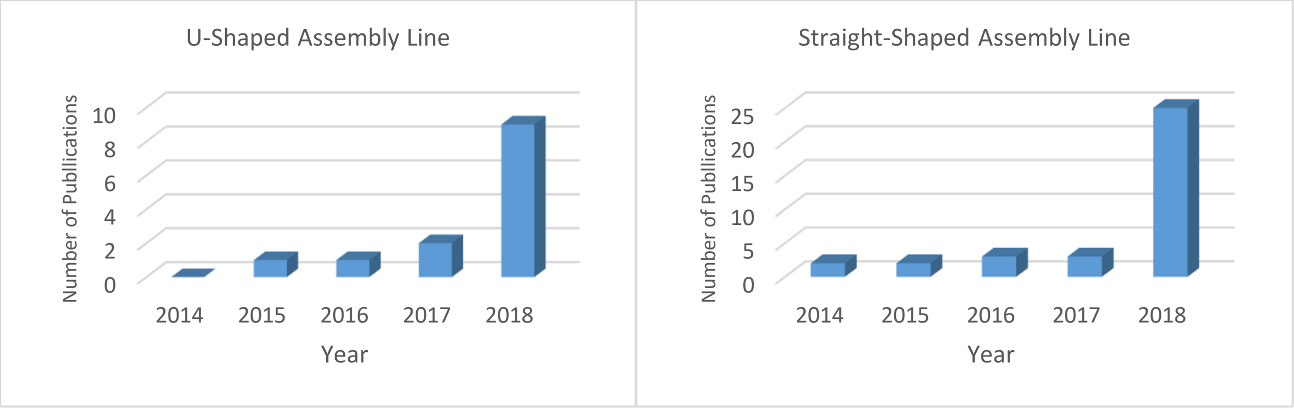
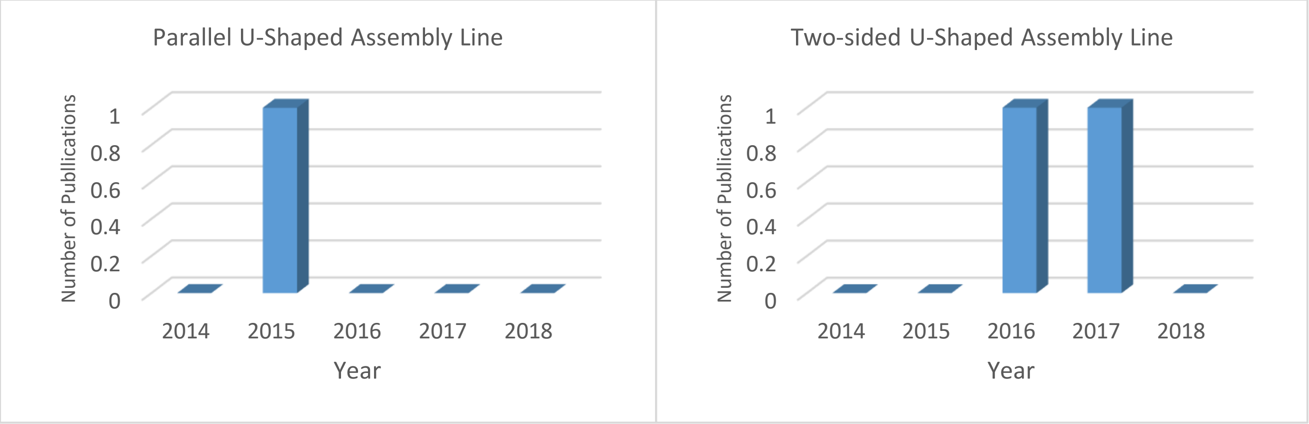


Fig. 3. Percentage of publications by layouts.



(a) StAL (b) U-Line



(c) PUAL (d) 2SUAL

Fig. 4. Publication trends on different layouts : (a) StAL, (b) U-Line, (c) PUAL and (d) 2SUAL.

The number of publications on the HL was 10 which composed of 7 papers from the P2SAL, 2 papers from the 2SUAL and 1 paper from the PUAL (Fig. 5). The first paper of the PUAL was available in 2015 and after that, there was no further publication. In contrast, the first paper of the 2SUAL was printed in 2016 and only one more was found in the year after. Hopefully, in 2019, there will be more paper on the PUAL and 2SUAL since the publication gaps are still available in these layouts.

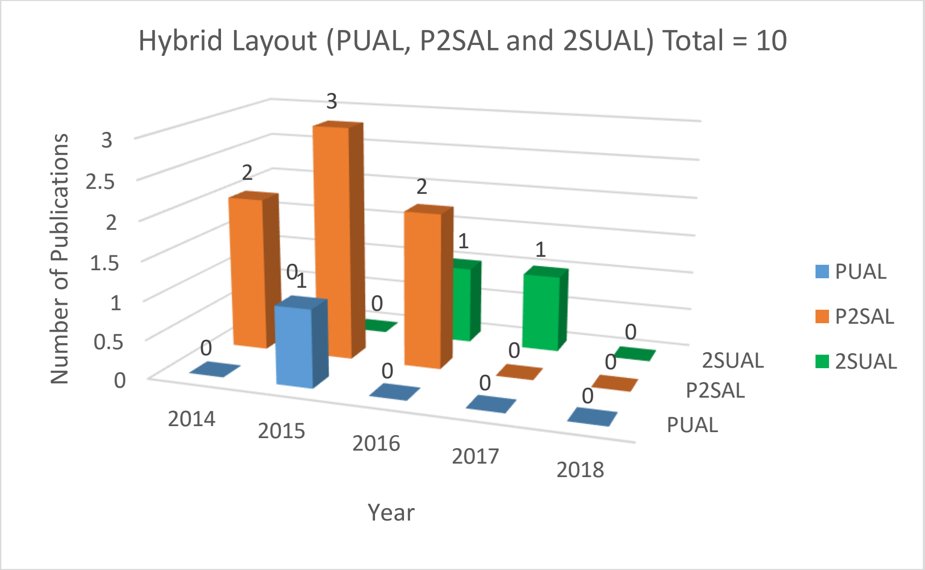


Fig. 5. Publications in hybrid layouts.

Types of problems

According to our description, the types of ALBPs were classified as I, II, O, E, F and Cost. Most of the papers attempted the problems Type I (52) and II (30) since both of them were standard types (Fig. 6). Problem's Type E was tackled least. Feasible solutions (Type F) were necessary as tentative solutions for every solution method before improving them to optimal solutions. Problem's Type O which included the optimisation of smoothness index, energy consumption, etc. have gained higher popular recently.

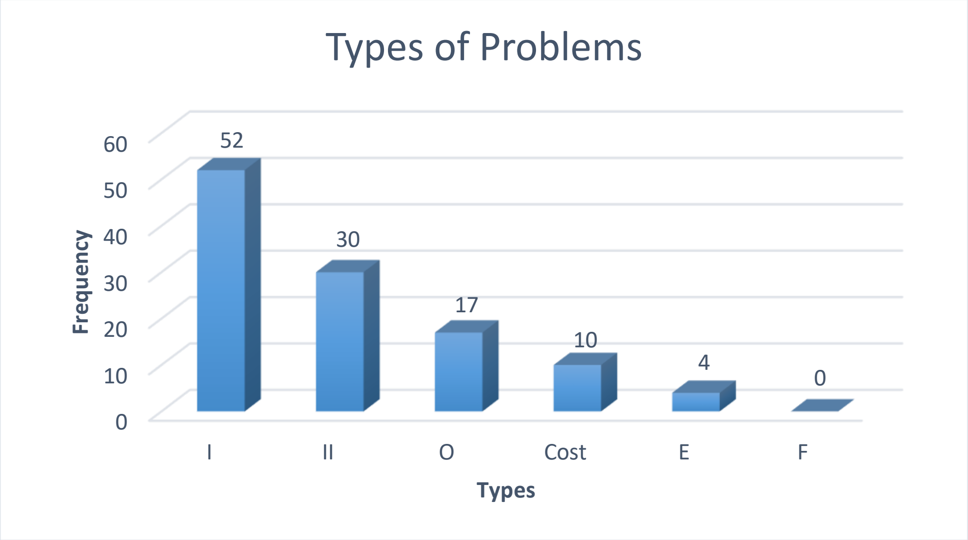


Fig. 6. Types of the ALBPs.

Number of objectives

Optimising the ALBP could be done with single and multiple objectives. Figure 7 showed that 48 and 59 papers published recently attempted single and multiple objectives, respectively. Multiple objectives became more popular than the single one. Among the multiple objective problems, most publications were focussed on bi-objective. Besides, only 1 paper on the P2SAL attempted four objective functions.

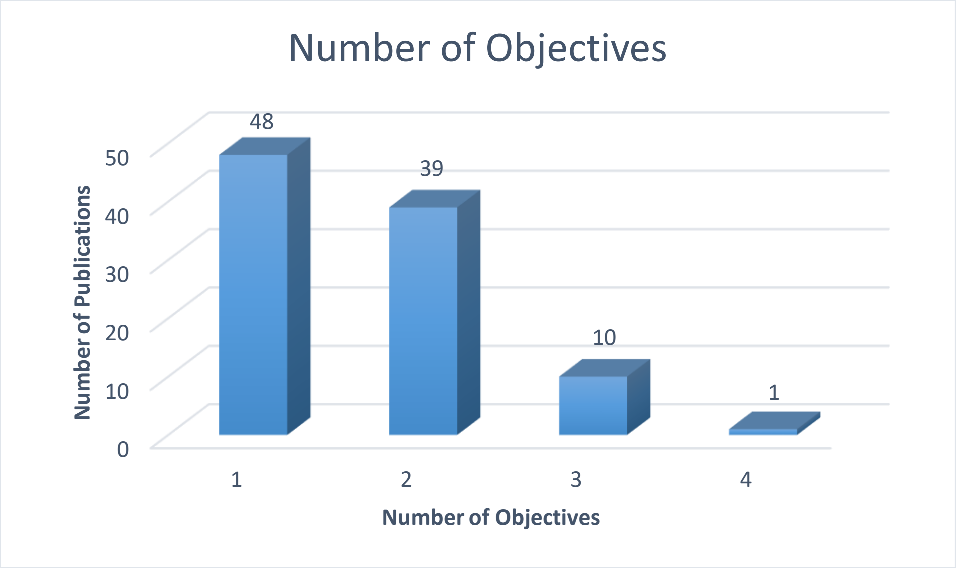


Fig. 7. The number of objectives.

Solution techniques

Since the ALBPs are NP-hard, it was not surprising that meta-heuristics were the most popular practice in solving the problems especially for medium- and large-sized problems (Fig. 8). The exact solution techniques were normally applicable for small-sized problems and they were formulated to demonstrate the relationship between model variables, decision variables and objective functions. Much less number of medium and large-scaled problems were solved by heuristics than meta-heuristics because of its effectiveness in comparison with the counterpart, particularly in the multi-objective optimisation problems. Figure 9 showed that among several meta-heuristics used to solve the ALBPs, the top three techniques were GA, SA and PSO, respectively. The total frequency that the meta-heuristics was applied was 73.

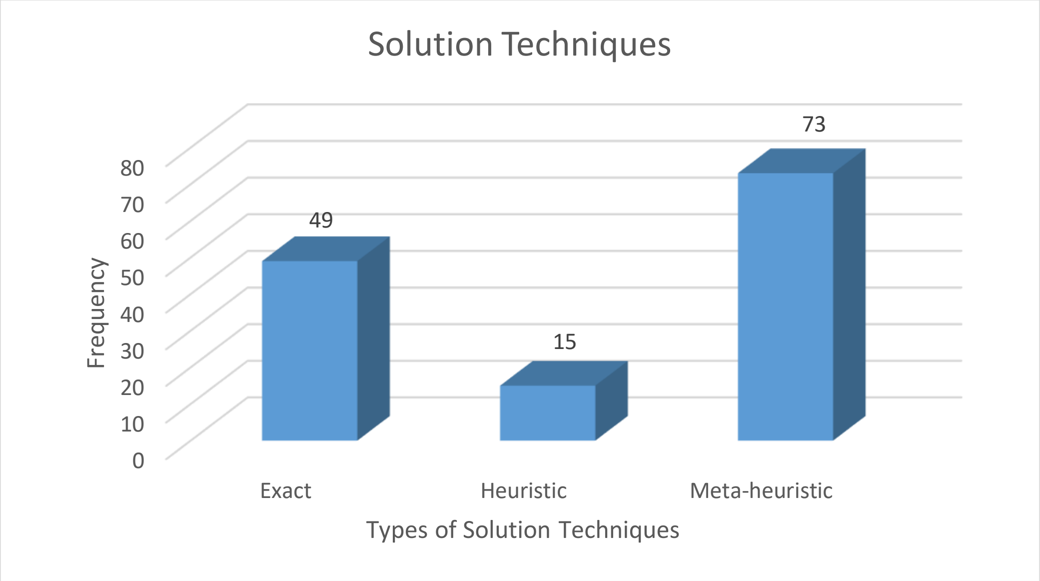


Fig. 8. Solution techniques.

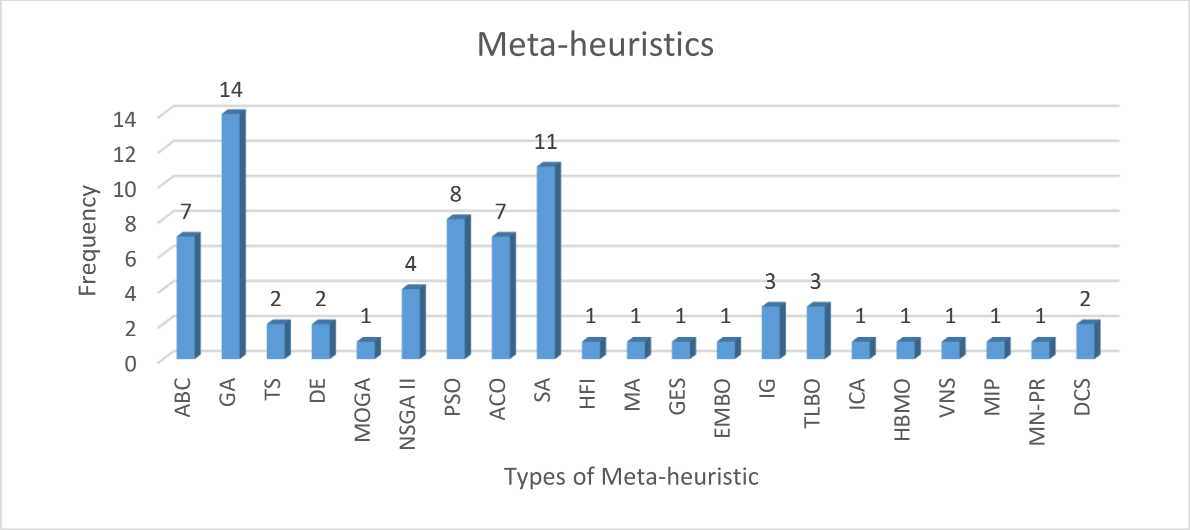


Fig. 9. Types of meta-heuristics.

Number of product models

Two-third of the papers assumed that there was only one model of the product being produced on the assembly lines for modelling simplicity (Fig. 10). Only 1 paper used multi-model assumption and around one-third of the papers focused on mixed-model assembly lines. Note that one paper in the StAL attempted both single and mixed models.

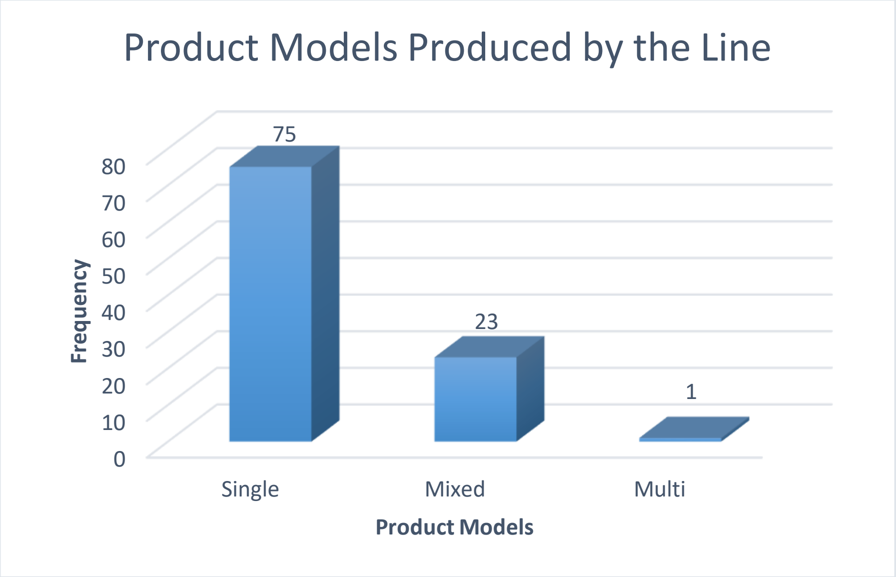


Fig. 10. Product models.

Operational constraint of task

Figure 11 showed that most of the publications paid no attention to the operational constraints of tasks. The positional constraint was applied in the models more often than positive, negative and synchronous constraints. The positional constraint was the mandatory requirement in the 2SAL, P2SAL and 2SUAL. Although the positional constraint was the optional requirement in the MAL, no paper in this layout employed such assumption (Fig. 12). Besides, all papers of the P2SAL (one type of the HAL) applied the positional constraint in their models. Figure 13 showed that the synchronous constraint was only found in the 2SAL although it could be used in the lines with multiple workers. The positive and negative zonings were applied equally (i.e. 14 each from Fig. 11). The positive and negative zonings were applied most in the 2SAL (Fig. 14). Moreover, these zoning constraints were mostly used in the P2SAL of the HAL.

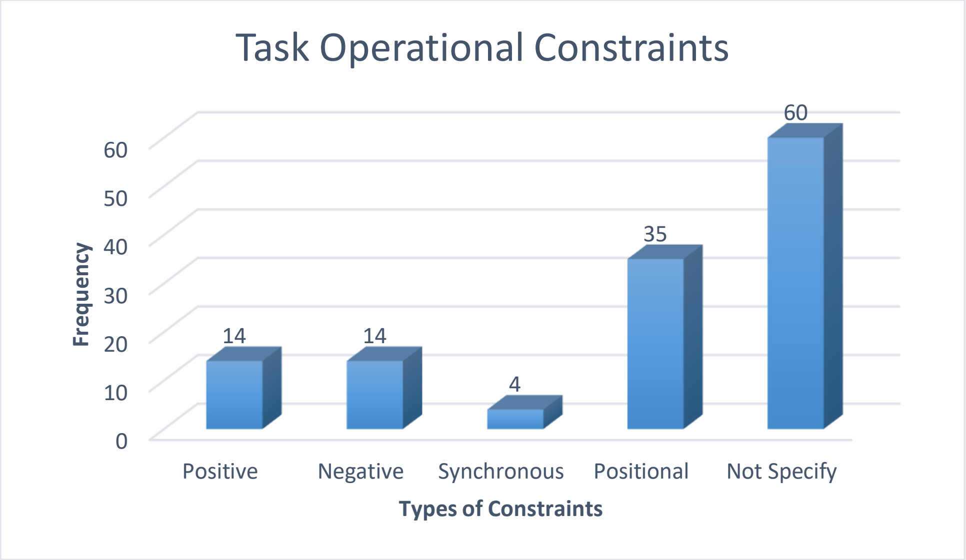


Fig. 11. Operational constraints of tasks.

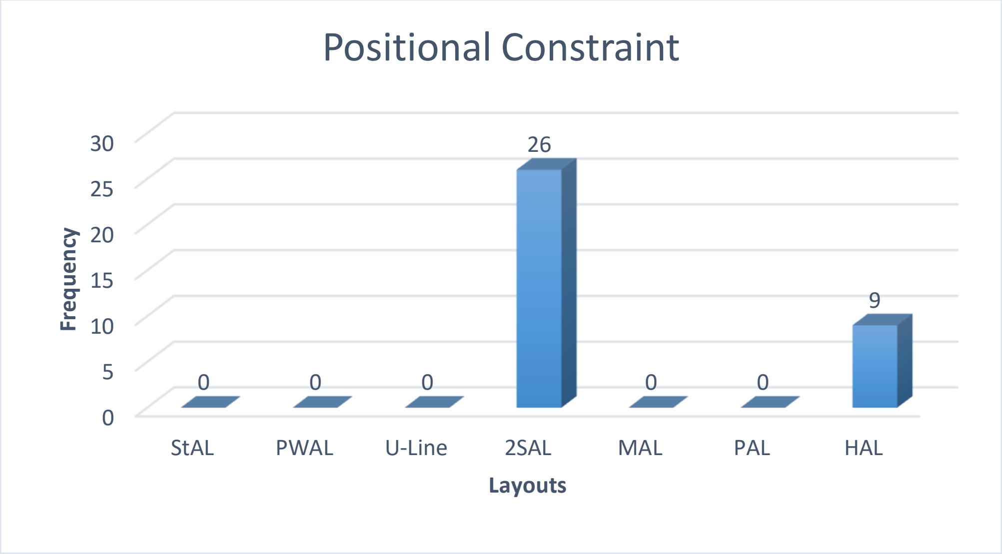


Fig. 12. Positional constraints used by different layouts.

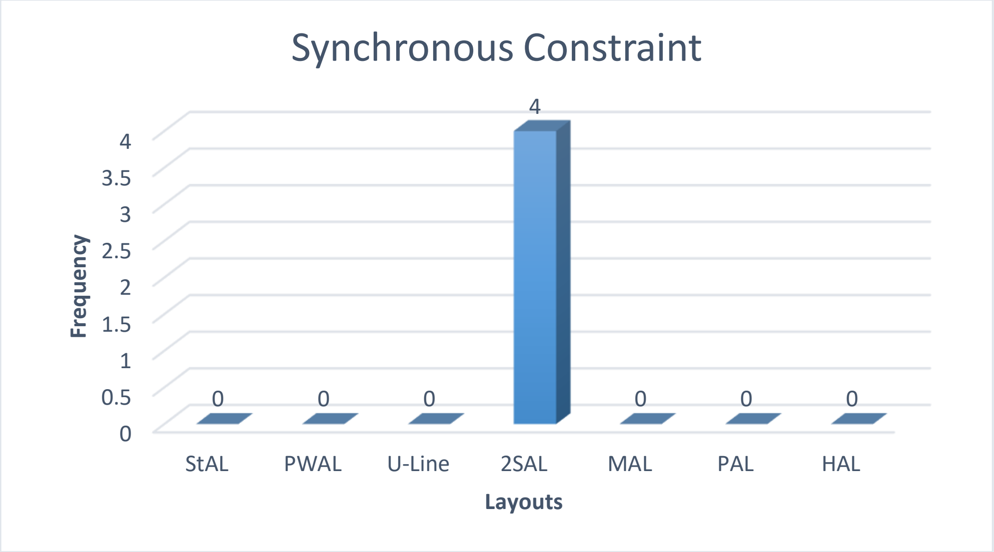


Fig. 13. Synchronous constraint.

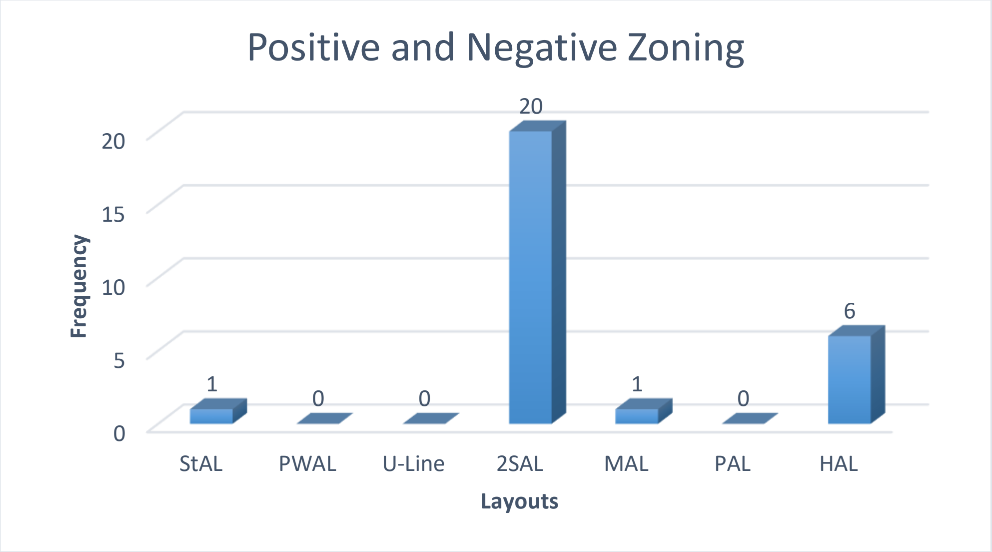


Fig. 14. Positive and negative constraints.

Characteristic of task time

Around two-thirds of the papers assumed fixed and deterministic task time in their model (Fig. 15). Also, the stochastic task time which followed some predefined probability distribution was used more than the dynamic one.

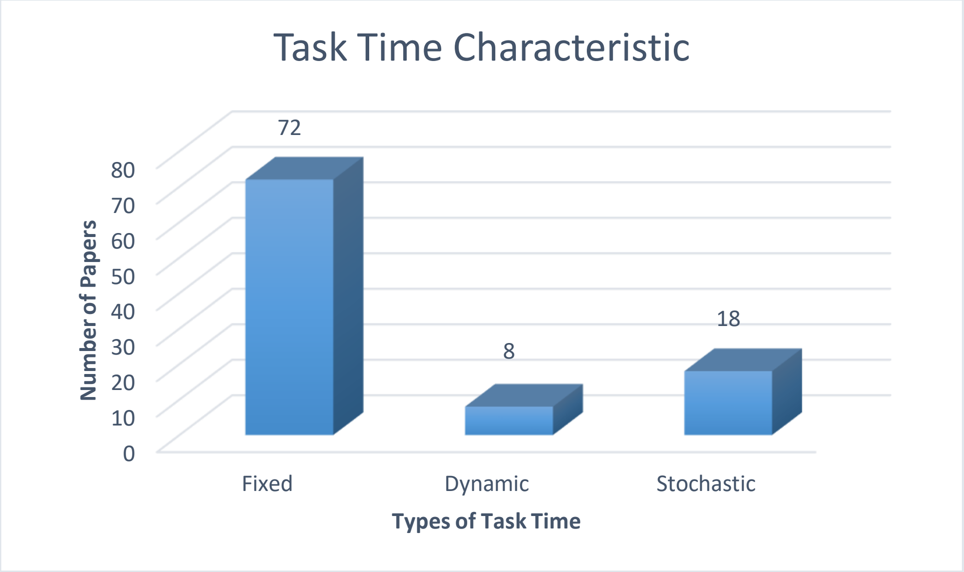


Fig. 15. Task time characteristic.

Real case problem

The total number of papers that referred to real industry cases was only 13 (Fig. 16). This amount was quite low compared with the total number of publications. The real case problems from industry were used most in the StAL followed by MAL, U-Line, 2SAL and PAL. None was found in the PWAL and HAL.

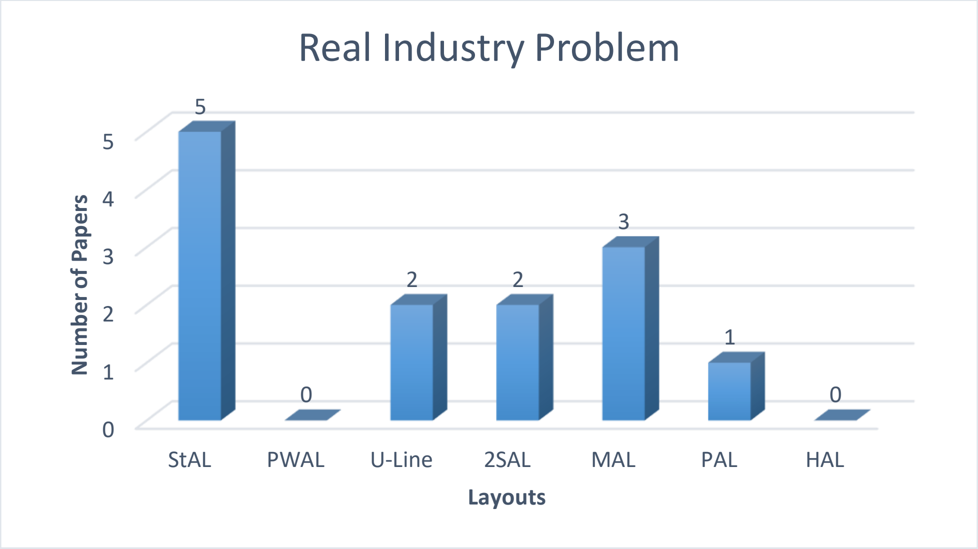


Fig. 16. Real case problem.

Simultaneous decision problem

The ALBP could be solved jointly with another decision problem to achieve a more synergistic and effective decision. The total number of papers that attempted joint decision-making problems was 17 (Fig. 17). The StAL and U-Line were the top two layouts fallen in this category.

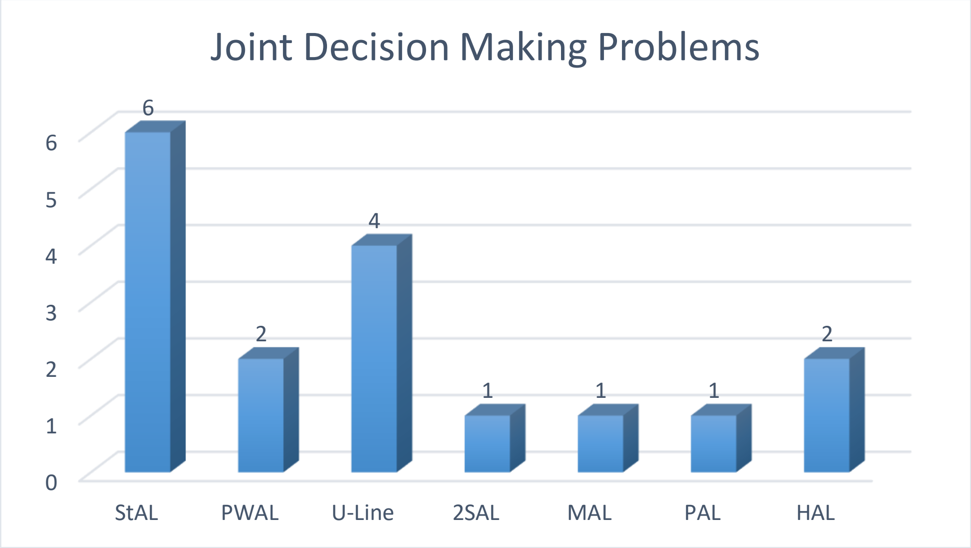


Fig. 17. Simultaneous decision problems.

Human Factor

Several human factors could be incorporated in the model of the ALBP, e.g. ergonomic risk, skill, and learning effect. It was observed that 11 papers from the StAL, U-Line and MAL encompassed such factors in the problems (Fig. 18).

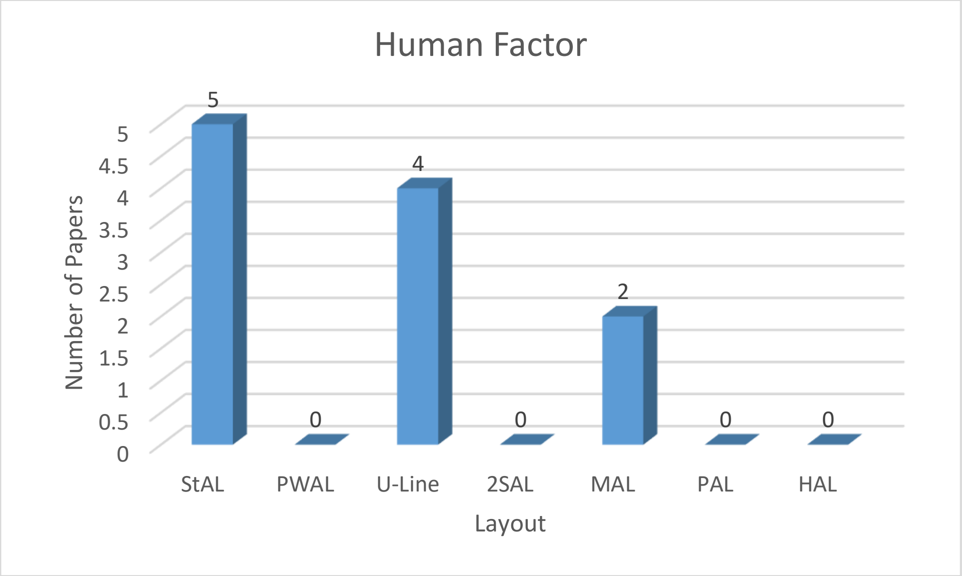


Fig. 18. Human factors.

11. Discussion for Future Research

From the papers published during the last five years, it was observed that the majority of the problems was in the StAL Type I aiming to optimise only a single objective using a meta-heuristic (GA). The assumptions were to produce a single product model on the line, fixed task time, no task operational constraint, not involve the human factor. The problem was a stand-alone type without any joint decision with another planning or operational problem of the assembly line. Moreover, the hypothetical problems were used in their case studies.

Plentiful evidence from the number and diversity of recent publications on the ALBPs indicates that this problem still induces much interest from both academicians and practitioners. As attention remains, the followings are some thoughts on future trends of the assembly line balancing research which merits the discussions.

- Most of the surveyed papers assumed that only a single product was produced on a single assembly line. This assumption was valid in the past when consumers were unavoidable to accept low-cost standardised products. Besides, to simplify the problem to be easier to start, this assumption is normally used for newly developed layouts. However, to effectively respond to today's diverse needs of customers as well as short product life-cycle, the multi- and mixed-model assembly lines in which two or more distinct models of a product are produced on the same line are a better way of production. Therefore, further research attention on multi- and mixed-model assembly lines are necessary especially with the newly emerged layouts.
- Multiple objective functions should be investigated rather than a single objective one to reflect actual operational requirements in the ALBPs. If clear domination between different objectives can be established, hierarchically optimising them is justifiable. However, in many cases where the objective functions are conflicted with each other, the solutions should be represented by Pareto optimal (non-dominated) solutions. The Pareto-based optimisation technique is among the most effective techniques to handle such a problem. Moreover, under this approach, a single solution that satisfies the preference of the decision-maker most could be selected.
- The ALBP Types O, E and Cost should be given more attention since not much research effort has been paid in these areas, possibly due to their non-linear functions. Moreover, the long-term impact of balancing decisions could be reflected through cost-oriented objectives so that the correlation between equipment cost, flexibility, cycle time and task time can be observed.
- Standard test problems, as well as real industry data with diverse instances varying in the number of tasks and precedence relationships which cover all vital characteristics in all layouts of assembly lines, must be established and make available to the ALB research community. As a result, newly-developed state-of-the-art solution methods can globally test and benchmark their relative performances on a common platform. This standard arena causes a fair competition among different contestant algorithms resulting in more reliable, consistency and credible results.
- State-of-the-art solution techniques should be adopted in solving large-scaled ALBPs. Apart from the popular algorithms, e.g. GA, SA and PSO, novel algorithms such as ACO, firefly optimisation algorithm (FOA), cuckoo optimisation algorithm (COA), honey bee mating optimisation algorithm (HBMO), etc. which has recently been developed should be tested against those well-known

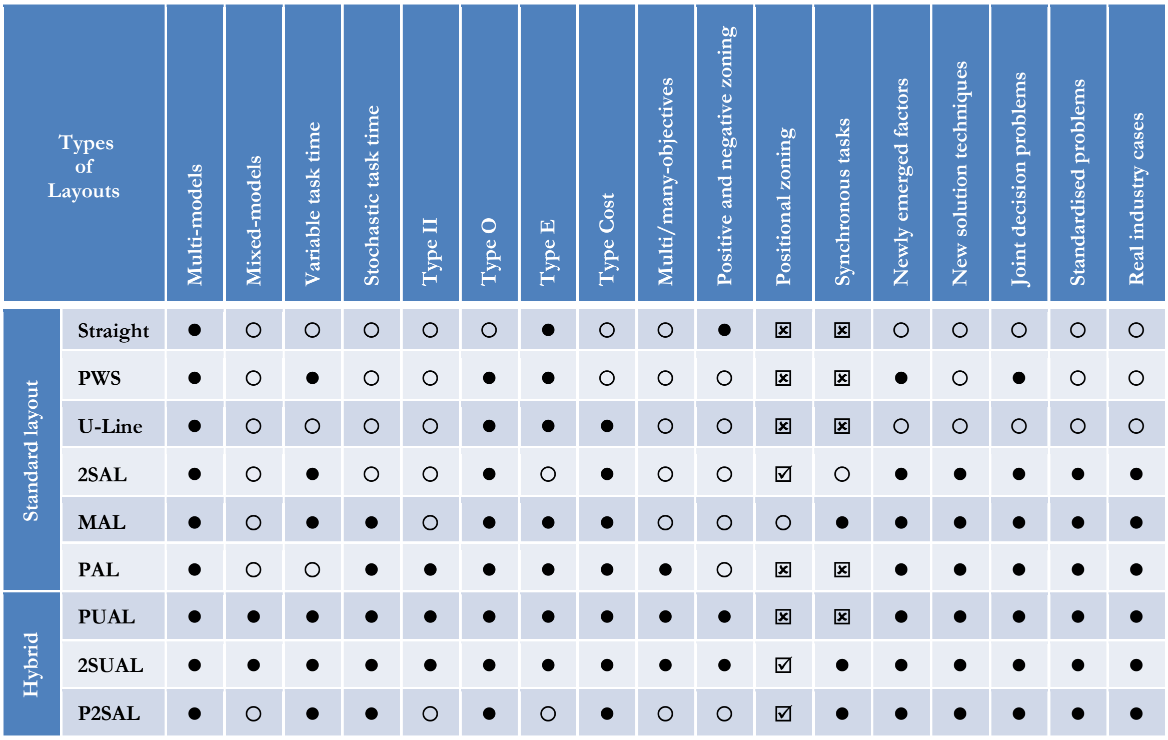
algorithms. Since in practice more than a single objective should be considered in the ALBP, multi/many-objective metaheuristics, such as NSGA III or MOEA/D, which could be applied in the standard or hybrid form to optimise the problems with more than three objectives simultaneously. To enhance the exploration and exploitation capability of the algorithm and also prevent premature convergence, some adaptive mechanism should be embedded. Also, the fuzzy numbers could be employed to effectively deal with imprecise, vague and uncertain task times if necessary.

- In the real industry, deterministic task time is rarely observed. The variation in task time may result from manual operation, learning effect, worker fatigue, lack of motivation, machine or equipment breakdown or poor maintenance, or defects from raw materials. As a result, variable and stochastic task times which reflect more realistic operations worth further consideration. Besides, different approaches to represent the uncertainties in task times should be used as appropriate, e.g. fuzzy variable, normal or some other distributions, or stochastic variable. Moreover, the ALBP with workstation-dependent and resource-dependent task times need further study.
- The task assignment constraints such as positive and negative zoning as well as synchronisation of tasks should be added into the model to reflect real industrial practices. Moreover, the synchronisation of tasks should be taken into account more on the MAL.
- The ALBPs should be jointly or multiple conducted with some other problems, such as sequencing, process selection, worker selection, or line design, so that a holistic view of the system and synergetic outcomes in terms of better performance, efficiency and effectiveness could be achieved.
- New crucial factors that are gaining popularity in this era such as energy conservation, carbon footprint, green production, disable and multi-skilled workers, learning curve effect, ergonomic risk, or lean manufacturing, should be taken into account in the ALBPs.
- The case studies and research surveys which explicitly describe the issues and how to deal with them when implementing line balancing techniques in the real world are necessary to demonstrate the validity of research findings and disclose the current practices of practitioners. This could guide academicians on the new constraints that should be incorporated into the problem. Also, to increase higher acceptance among practitioners, more effort should be spent on solving real industrial ALBPs rather than fictitious problems.
- Because the PUAL and 2SUAL are new layouts, only a few publications have been released. Therefore, interesting future research should be on the extension of their basic problem definitions to cover more complex elements in reality. Moreover, the study to show that such layouts are feasible to implement in real industry and bring about real benefits to production systems is needed.
- To facilitate the implementation of the ALB techniques in the real industry, user-friendly computer software embedded with many effective solution techniques has to be developed. This software should be flexible enough to encompass all requirements from every standard layout. Moreover, it would be much better if free downloads are allowed at least for the restricted version.

Figure 19 summaries the research gap that needs further attention in the ALBPs. The solid bullet point (●) means the research activity is highly needed and the hollow bullet point (○) means moderate need. Besides, ☑ means a must-have constraint and ☒ means a non-applicable constraint.

12. Conclusions

The ALBPs continues to be the topic that draws great attention from both research scholars and practitioners as revealed by the recent number of publications. This brings about the need for a comprehensive survey of the latest research (2014-2018) on the ALBPs to identify the trends of the problems and appropriate solution methodologies. Factual findings are discussed with graphical illustration. Some thought on potential future research is also articulated. As observed during the survey, many configurations of the assembly lines, particularly the hybrid forms, have been put forward to increase the utilisation and effectiveness of the systems. However, it is astonishing that only 13 out of 98 papers explicitly report on the implementations of the systems in real industries in which none is from the hybrid layouts. This highlights that there still be a big gap between the practical and theoretical aspects of the ALBPs. As a result, the actual requirements and operating conditions from industry must be taken into account seriously in extending the models of the ALBPs to bridge the gap and increase acceptance from practitioners.



Types of Layouts		Multi-models	Mixed-models	Variable task time	Stochastic task time	Type II	Type O	Type E	Type Cost	Multi/many-objectives	Positive and negative zoning	Positional zoning	Synchronous tasks	Newly emerged factors	New solution techniques	Joint decision problems	Standardised problems	Real industry cases
Standard layout	**Straight**	●	○	○	○	○	○	●	○	○	●	☒	☒	○	○	○	○	○
	PWS	●	○	●	○	○	●	●	○	○	○	☒	☒	●	○	●	○	○
	U-Line	●	○	○	○	○	●	●	●	○	○	☒	☒	○	○	○	○	○
	2SAL	●	○	●	○	○	●	○	●	○	○	☑	○	●	●	●	●	●
	MAL	●	○	●	●	○	●	●	●	○	○	○	●	●	●	●	●	●
	PAL	●	○	○	●	●	●	●	●	●	○	☒	☒	●	●	●	●	●
Hybrid	**PUAL**	●	●	●	●	●	●	●	●	●	●	☒	☒	●	●	●	●	●
	2SUAL	●	●	●	●	●	●	●	●	●	●	☑	●	●	●	●	●	●
	P2SAL	●	○	●	●	○	●	○	●	○	○	☑	●	●	●	●	●	●

Fig. 19. The research gap in the ALBPs.

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◆

Parames Chutima, photograph and biography not available at the time of publication.

Table 1. Summarised research on the StAL.

Year	Author	Problem Type	Objective	Solution Technique	Characteristic				Simultaneous Decision	Real Case	Robotic
					Product	Task	Task Time	Operator			
2014	Otto and Otto [7]	Type I	N	H (PRBMs)	Single	-	Fixed	-	-	-	-
2014	Saif et al. [8]	Type O	1. O (Min. workload for different models in each workstation) 2. O (Min. the deviation of workload on a workstation from the average of the workload of all workstations)	MH (Multi-ABC)	Mixed	-	Fixed	-	Sequencing	-	-
2015	Al-Hawari et al. [9]	Type I	1. N 2. E 3. O (Min. workload variation between workstations)	MH (MA-GA)	Single	-	Fixed	-	-	-	-
2015	Sungur and Yavuz [10]	Type Cost	O (Total cost)	E (ILP)	Single	Worker dependent	Dynamic	Qualification levels of workers	-	-	-
2016	Alavidoost et al. [12]	Type I	1. N 2. C	E (BOFMILP)	Single	-	Stochastic	-	-	-	-

Year	Author	Problem Type	Objective	Solution Technique	Characteristic				Simultaneous Decision	Real Case	Robotic
					Product	Task	Task Time	Operator			
2016	Buyukozkan et al. [11]	Type O	1. O (Min. weighted workload of the most heavily loaded workstation) 2. N	MH (ABC), MH (TS)	Mixed	-	Fixed	-	-	-	-
2016	Pınarbaşı et al. [13]	Type O	O (Min. smoothness index value)	E (Integrated CP and QN)	Single	-	Stochastic	-	-	-	-
2017	Akpinar et al. [16]	Type I	N	E (BDA)	Single and Mixed	-	Fixed	-	-	-	-
2017	Li and Boucher [17]	Type I	N	H (BIR)	Single	-	Dynamic	-	-	-	✓
2017	Nilakantan et al. [15]	Type Cost and Type II	1. C 2. Cost (Total assembly line cost)	E (IP), MH (DE)	Single	-	Fixed	-	-	-	✓
2018	Azizoğlu and Imat [16]	Type O	O (Min. sum of the squared deviations of the workstation loads around the cycle time)	E (MILP), E (B&B)	Single	-	Fixed	-	-	-	-
2018	Babazadeh et al. [36]	Type I, Type II	1. N 2. C	MH (MOGA), base FP), MH (NSGA-II)	Single	-	Stochastic	-	-	-	-

Year	Author	Problem Type	Objective	Solution Technique	Characteristic				Simultaneous Decision	Real Case	Robotic
					Product	Task	Task Time	Operator			
2018	Borba et al. [28]	Type II	C	E (MILP), E (BBR), H (IBS)	Single	Robot dependent	Dynamic	-	-	-	✓
2018	Bukchin and Raviv [20]	Type I, Type II	1. N 2. C	E (MILP), E (CP)	Single	-	Fixed	-	-	-	-
2018	Dong et al. [33]	Type II	1. C 2. Cost (Equipment cost)	E (Bi-objective chance-constraint MILP), MH (Hybrid PSO/SA)	Single	Negative zoning	Stochastic	-	-	-	-
2018	Efe and Kurt [40]	Type I, Type O	1. N 2. O (Max. total closeness coefficient of personnel while executing the line balancing)	H (IT2TrF-based TOPSIS)	-	-	Stochastic	-	-	✓ (Textile firm)	-
2018	Fathi et al. [19]	Type I	N	H (Constructive heuristics)	Single	-	Fixed	-	-	-	-
2018	Foroughi and Gökçen [46]	Type Cost	Cost (Total cost of one unit)	MH (Multiple rule-based GA)	Single	-	Stochastic	-	-	-	-
2018	Huo et al. [34]	Type I	N	MH (ACO-BS)	Single	-	Fixed	-	-	-	-

Year	Author	Problem Type	Objective	Solution Technique	Characteristic				Simultaneous Decision	Real Case	Robotic
					Product	Task	Task Time	Operator			
2018	Kim et al. [18]	Type Cost, Type C, Type O	1. Cost (Total cost of the sum of the workstation costs and labour costs of skilled and unskilled temporary workers) 2. C 3. O (Work overload)	E (ILP), E (MILP), MH (HGA)	Mixed	Skill dependent task time	Dynamic	Unskilled temporary workers	Unskilled temporary workers	✓(Automobile company in Korea)	-
2018	Lai et al. [37]	Type E	E	H (STABRAD)	Single	-	Fixed	-	-	-	-
2018	Leitold et al. [39]	Type II	C	H (EWSD)	Single	-	Stochastic	-	-	-	-
2018	Li et al. [21]	Type II	C	E (MILP), MH (SA), MH (RSA)	Single	-	Fixed	-	-	✓	✓
2018	Li et al. [22]	Type II	C	E (MILP), MH (RSA), MH (RCoGA)	Mixed	-	Fixed	-	Sequencing and robot allocation	-	✓
2018	Mardani-Fard et al. [35]	Type Cost	1. Cost (Equipment purchasing cost), 2. O (Worker time-dependent wage), 3. O (Average task performing	E (Hybrid FP& GP)	Single	Worker dependent	Stochastic	Worker skill	-	-	-

Year	Author	Problem Type	Objective	Solution Technique	Characteristic				Simultaneous Decision	Real Case	Robotic
					Product	Task	Task Time	Operator			
			quality of the assembly line)								
2018	Nilakantan et al. [23]	Type O	O (Energy consumption of the line)	MH (PSO), MH (DE)	Single	-	Fixed	-	-	-	✓
2018	Pereira [30]	Type Cost	Cost (weighted sum of costs associated with stations and resources)	E (MILP), H (Hoffman &EDA)	Multi	-	Fixed	-	-	✓ (Apparel company in Chili)	-
2018	Pereira [31]	Type II	C	E (MILP), H (Heuristic)	Single	Worker dependent	Stochastic	Various skills	Worker assignment	-	-
2018	Pereira et al. [29]	Type Cost	Cost (The installation and operations costs)	MH (Hybrid GA&MA)	Single	-	Fixed	-	Task assignment and equipment decisions	-	✓
2018	Pereira and Álvarez-Miranda [32]	Type I	N	E (BBR)	Single	-	Stochastic	-	-	-	-
2018	Ritt and Costa [27]	Type I, Type II	1. N 2. C	E (IP)	Single	-	Fixed	-	-	-	-

Year	Author	Problem Type	Objective	Solution Technique	Characteristic				Simultaneous Decision	Real Case	Robotic
					Product	Task	Task Time	Operator			
2018	Salehi et al. [24]	Type I	1. N 2. Cost (Total cost of the assembly line including labour and necessary equipment), 3. O (Min. total disqualification level of the stations)	E (MILP), MH (HFI)	Single	Worker dependent	Stochastic	Worker's performance and quality	Skill and qualification level	✓ (Garment production industries)	-
2018	Yuan et al. [25]	Type I, Type O	1. N 2. O (Min. smoothness index)	MH (MA)	Single	-	Fixed	-	-	-	-
2018	Zhang [38]	Type I	1. N 2. O (Smooth index)	MH (IGA)	Single	-	Fixed	-	-	✓ (Antenna assembly shop)	-
2018	Zhou and Wu [41]	Type II	C	MH (ASAGA)	Single	-	Fixed	-	-	✓ (Car body welding assembly line)	✓

Table 2. A summarised research on the PWAL.

Year	Author	Problem Type	Objective	Solution Technique	Characteristic				Simultaneous Decision	Real case	Robotic
					Product	Task	Task time	Operator			
2015	Tiacci [44]	Type Cost	1. Cost (Total annual cost for labour, equipment and buffers) 2. Cost (Realised cycle time)	MH (GA)	Mixed	-	Stochastic	-	Buffer allocation	-	-
2015	Öztürk et al. [43]	Type II	C	E (CP)	Mixed	-	Fixed	-	Cyclic scheduling	-	-
2016	Rabbani et al. [45]	Type I	1. N 2. O (Max. workload smoothness)	MH (NSGA-II), MH (MOPSO)	Mixed	-	Fixed	-	-	-	-

Table 3. A summarised research on the U-line.

Year	**Author**	**Problem Type**	**Objective**	**Solution Technique**	**Characteristic**				**Simultaneous Decision**	**Real Case**	**Robotic**
					Product	**Task**	**Task time**	**Operator**			
2015	Fattahi and Turkay [46]	Type Cost	Cost (Total assignment cost)	E (MILP)	Single	-	Fixed	-	-	-	-
2016	Alavidoost et al. [12]	Type I	1. N 2. C	E (BOFMILP)	Single	-	Stochastic	-	-	-	-
2017	Li et al. [47]	Type II	C	E (IP), H (Rule-based heuristic)	Single	-	Fixed	-	-	-	-
2017	Oksuz et al. [48]	Type E	E	MH (ABC), MH (GA)	Single	Worker dependent	Dynamic	Worker's performance	Worker assignment	✓ (Tractor assembly line)	-
2018	Babazadeh et al. [36]	Type I	1. N 2. C	E (FLP), MH (Enhanced NSGA-II)	Single	-	Stochastic	-	-	-	-
2018	Fathi et al. [19]	Type I	N	H (Constructive heuristics)	Single	-	Fixed	-	-	-	-
2018	Li et al. [22]	Type I	N	E (BBR)	Single	-	Fixed	-	-	-	-
2018	Nejad et al. [51]	Type I	N	MH (GES)	Single	-	Fixed	-	-	-	-
2018	Wang et al. [50]	Type II	1. C 2. O (workload balancing of each workstation) 3. O (average value of the standard deviation of	E (MNILP), MH (GA)	Mixed	-	Stochastic	Learning effect	-	✓ (Assembly line BSY-75/90)	-

Year	Author	Problem Type	Objective	Solution Technique	Characteristic				Simultaneous Decision	Real Case	Robotic
					Product	Task	Task time	Operator			
			the operation time)								
2018	Zhang et al. [54]	Type II	1. C	MH (EMBO)	Single	Worker dependent	Dynamic	Worker' skill	Worker allocation	-	-
2018	Zhang et al. [55]	Type II	1. C 2. O (Energy consumption)	E (NMMIP), MH (PABC)	Single	Robot dependent	Dynamic	Selected robot	Robot assignment	-	✓
2018	Zhang et al. [52]	Type II	1. C 2. O (Task assignment alteration)	MH (NSGA-II), MH (MOSA)	Single	-	Fixed	-	-	-	-
2018	Zhang et al. [53]	Type I	C	MH (IG)	Single	Worker dependent	Dynamic	Worker' skill	Worker allocation	-	-

Table 4. A summarised research on the 2SAL.

Year	Author	Problem Type	Objective	Solution Technique	Characteristic				Simultaneous Decision	Real case	Robotic
					Product	Task	Task time	Operator			
2014	Aghajani et al. [60]	Type II	C	E (MIP), MH (SA)	Mixed	Positive zoning, Negative zoning, Positional zoning	Dynamic (depend on the selected robot)	Different performance of robots	Robot selection	-	✓
2014	Jawahar et al. [56]	Type I	1. N 2. O (Min. unbalance time among workstations)	H (EHA), MH (SA)	Single	Positional zoning	Fixed	-	-	-	-
2014	Purnomo and Wee [59]	Type O	1. O (Max. production rate) 2. O (Max. distributed workload)	H (HS)	Single	Positive zoning, Negative zoning, Positional zoning	Fixed	-	-	-	-
2014	Tuncel and Aydin [57]	Type I	1. N 2. O (Balance workload among workstations)	MH (TLBO)	Single	Positive zoning, Negative zoning, Positional zoning	Fixed	-	-	✓(International home appliances company)	-
2014	Wang et al. [58]	Type I	1. N 2. O (Line length)	MH (Hybrid ICA with LAHC)	Single	Positive zoning, Negative zoning, Positional zoning	Fixed	-	-	✓ (Engineering machinery company)	-

Year	Author	Problem Type	Objective	Solution Technique	Characteristic				Simultaneous Decision	Real case	Robotic
					Product	Task	Task time	Operator			
2015	Yuan et al. [61]	Type I	1. N 2. O (Min. number of mated-stations)	E (IP), H (LAHC)	Single	Positive zoning, Negative zoning, Positional zoning, Synchronise constraint	Fixed	-	-	-	-
2015	Yuan et al. [62]	Type I	1. N 2. O (Min. the number of mated-stations)	MH (Hybrid HBMO with SA)	Mixed	Positional zoning	Fixed	-	-	-	-
2016	Chiang et al. [64]	Type I	1. N 2. O (Min. line length)	MH (PSO)	Single	Positional zoning	Stochastic	-	-	-	-
2016	Lei and Guo [63]	Type II	C	MH (VNS)	Single	Positional zoning	Fixed	-	-	-	-
2016	Li et al. [68]	Type E	1. E 2. O (Min. smoothness index) 3. Cost (Min. of total relevant costs per product unit)	MH (MITLBO)	Single	Positive zoning, negative zoning, Positional zoning, Synchronous constraint	Fixed	-	-	-	-
2016	Li et al. [69]	Type II	C	E (MIP), MH (C-PSO)	Single	Robot dependent, Positive zoning, Negative zoning, Positional zoning	Fixed	Assigned robot	-	-	✓

Year	Author	Problem Type	Objective	Solution Technique	Characteristic				Simultaneous Decision	Real case	Robotic
					Product	Task	Task time	Operator			
2016	Li et al. [70]	Type II	1. C 2. O (Min. energy consumption)	E (MIP), MH (RSA)	Single	Robot dependent, Positive zoning, Negative zoning, Positional zoning	Fixed	Assigned robot	Energy consumption	-	✓
2016	Li et al. [71]	Type II	C	E (IP), MH (IG)	Single	Positive zoning, Negative zoning, Positional zoning	Fixed	-	-	-	-
2016	Sepahi and Naini [65]	Type II	C	E (MIP), H (Heuristic)	Single	Positional zoning, Parallel task performance properties	Fixed	-	-	✓ (Locomotive production plant)	-
2016	Tang et al. [66]	Type II	1. C 2. O (Total overload and underload)	MH (DABC)	Single	Positional zoning	Fixed	-	-	-	-
2016	Yang et al. [67]	Type I	1. N 2. O (Min no. of mated-station)	MH (MN-PR)	Single	Positional zoning	Fixed	-	-	-	-
2017	Delice et al. [73]	Type I	1. N 2. O (Min. number of mated stations	MH (PSO)	Mixed	Positional zoning	Fixed	-	-	-	-
2017	Li et al. [72]	Type I	N	MH (IG), H (modified NEH)	Single	Positional zoning	Fixed	-	-	-	-

Year	Author	Problem Type	Objective	Solution Technique	Characteristic				Simultaneous Decision	Real case	Robotic
					Product	Task	Task time	Operator			
2017	Tang et al. [74]	Type I	1. N 2. O (Min. number of mated station)	MH (HTLBO)	Single	Positive zoning, Negative zoning, Positional zoning	Stochastic	-	-	-	-
2018	Duan et al. [76]	Type II	C	MH (IABC)	Single	Positional zoning	Fixed	-	-	-	-
2018	Hu and Wu [75]	Type O	O (Finish time-based smoothness) O (Finish time-based MAD)	H (Heuristic)	Single	Positional zoning	Fixed	-	-	-	-
2018	Kucukkoc et al. [80]	Type I	1. N 2. O (No.of mated stations)	MH (ACO)	Mixed	Positive zoning, Negative zoning, Positional zoning	Fixed	-	-	-	-
2018	Li et al. [78]	Type II	1. C 2. O (Relative percentage deviation)	MH (DCS), MH (CoCS)	Single	Positional zoning, Robot dependent	Fixed	Selected robot	Robot allocation	-	✓
2018	Li and Coit [77]	Type O	O (Min. no. of positions)	E (PR_BDP)	Single	Positional zoning	Fixed	-	-	-	-
2018	Li et al. [79]	Type E	1. E 2. O (Weighted smoothness index) 3. O (Total relevant costs	MH (MOHICA)	Mixed	Positive zoning, Negative zoning, Synchronous constraint,	Fixed	-	-	-	-

Year	Author	Problem Type	Objective	Solution Technique	Characteristic				Simultaneous Decision	Real case	Robotic
					Product	Task	Task time	Operator			
			per unit of product)			Positional zoning					

Table 5. A summarised research on the MAL.

Year	**Author**	**Problem Type**	**Objective**	**Solution Technique**	**Characteristic**				**Simultaneous Decision**	**Real Case**	**Robotic**
					Product	**Task**	**Task time**	**Operator**			
2015	Kellegöz and Toklu [81]	Type O	O (Min no. of worker)	E (IP), H (COH), MH (GASA)	Single	-	Fixed	-	-	-	-
2017	Kellegöz [82]	Type I, Type O	1. N 2. O (Min no. of worker)	E (MIP), MH (SA)	Single	-	Fixed	-	-	-	-
2017	Roshani and Nezami [83]	Type I, Type O	1. N 2. O (Min. no. of worker)	E (MIP), MH (SA)	Mixed	-	Fixed	-	-	-	-
2017	Roshani and Giglio [84]	Type II, Type O	1. C 2. O (Min no. of workers)	E (MIP), MH (ISA), MH (DSA)	Single	-	Fixed	-	-	-	-
2018	Alghazi and Kurz [86]	Type I	N	E (IP), E (CP)	Mixed	Negative zoning	Fixed	Ergonomics risks	-	✓ (An automotive industry)	
2018	Chen et al. [87]	Type I, Type O	1. N 2. O (Min. no. of operators) 3. O (Min. no. of resources)	E (MIP), H (HH)	Single	Worker dependent	Fixed	Skilled operators	Resource-constraints	✓ (An automobile assembly plant)	-
2018	Naderi et al. [85]	Type O	O (Min. no. of workers)	E (MIP)	Mixed	-	Fixed	-	-	✓ (Fiat Chrysler automotive)	-

Table 6. A summarised research on the PAL.

Year	**Author**	**Problem Type**	**Objective**	**Solution Technique**	**Characteristic**				**Simultaneous Decision**	**Real Case**	**Robotic**
					Product	**Task**	**Task time**	**Operator**			
2014	Hemig et al. [88]	Type Cost	Cost (Cost of production plan)	E (NMIP), E (DP)	Mixed	-	Fixed	-	Staff planning	✓ (A final assembly shop in an automotive plant)	-
2014	Rabbani et al. [89]	Type II	C (Min. average stochastic cycle time for two lines)	MH (HGA)	Mixed	-	Fixed	-	-	-	-
2017	Rabbani et al. [90]	Type I	N	MH (PSO)	Mixed	-	Stochastic	-	-	-	-
2018	Özcan [91]	Type I	N	E (CPMIP), MH (TS)	Single	-	Stochastic	-	-	-	-

Table 7. A summarised research on the HAL.

Year	Author	Problem Type	Objective	Solution Technique	Characteristic				Simultaneous Decision	Real Case	Robotic
					Product	Task	Task time	Operator			
					PUAL						
2015	Kucukkoc and Zhang [92]	Type I	N	H (Heuristic)	Single	-	Fixed	-	-	-	-
					P2SAL						
2014	Kucukkoc and Zhang [93]	Type I	N	MH (ABACO/S)	Mixed	Positional zoning	Fixed	-	Sequencing	-	-
2014	Kucukkoc and Zhang [94]	Type I	1. N (Min. line length) 2. O (Min. idle times of the stations) 3. N (Min. workload smoothness)	E (IP), MH (ABACO/S)	Mixed	Positive zoning, Negative zoning, Positional zoning	Fixed	-	Sequencing	-	-
2015	Kucukkoc and Zhang [92]	Type I	N	E (IP), MH (GA)	Single	Positive zoning, Negative zoning, Positional zoning	Fixed	-	-	-	-
2015	Kucukkoc and Zhang [95]	Type E	1. C 2. N	MH (ACO)	Single	Positional zoning	Fixed	-	-	-	-
2015	Ağpak and Zolfaghari [97]	Type I, Type II, Type Cost, Type O	1. N 2. C 3. Cost 4. O (Min. number of positions)	E (MIP)	Single	Positive zoning, Negative zoning, Positional zoning,	Fixed	-	-	-	-

Year	Author	Problem Type	Objective	Solution Technique	Characteristic				Simultaneous Decision	Real Case	Robotic
					Product	Task	Task time	Operator			
						Task synchronisation					
2016	Kucukkoc and Zhang [96]	Type I	1. O (Line length) 2. N	MH (ACO)	Mixed	Positional zoning	Fixed	-	-	-	-
2016	Tapkan et al. [98]	Type I, Type O	1. N 2. O (Best balance among the solutions which are the same number of stations) 3. O (Min. transition between lines)	MH (BA), MH (ABC)	Single	Positional zoning	Fixed	-	-	-	-
2SUAL											
2016	Delice et al. [99]	Type I, Type O	1. N 2. O (Min. the number of positions)	MH (GA)	Single	Positional zoning	Stochastic	-	-	-	-
2017	Delice et al. [100]	Type I, Type O	1. N 2. O (Min. the number of positions)	MH (PSO)	Single	Positional zoning	Fixed	-	-	-	-