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Abstract: Assembly lines are mass production systems which are significant in the industrial production of both standard and customised products. Currently, industrial companies offer several products and it is common for an assembly system to have multiple assembly lines. Parallel assembly lines are multiple lines located in such a way as to allow improvements in the system's efficiency through the use of common resources. In recent years several research studies have been made on parallel assembly lines. In this paper, we survey the parallel assembly lines balancing problem (PALBP) studies. Moreover, a classification scheme is provided to ease understanding. Finally, the main gaps in the literature are described and future research directions are presented.

Highlights (for review)

A review literature of the parallel assembly lines is carried out.

The literature is classified according to a classification scheme proposed.

Advantages and disadvantages of the parallel assembly lines are presented.

The suggestions for future research directions are provided.

A survey of the Parallel Assembly Lines Balancing Problem

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Abstract

Assembly lines are mass production systems which are significant in the industrial production of both standard and customised products. Currently, industrial companies offer several products and it is common for an assembly system to have multiple assembly lines. Parallel assembly lines are multiple lines located in such a way as to allow improvements in the system's efficiency through the use of common resources. In recent years several research studies have been made on parallel assembly lines. In this paper, we survey the parallel assembly lines balancing problem (PALBP) studies. Moreover, a classification scheme is provided to ease understanding. Finally, the main gaps in the literature are described and future research directions are presented.

Keywords

Assembly line balancing; Multiple lines; Parallel lines; Survey; Review; State-of-the-art.

1. Introduction

Assembly lines are a flow-oriented production system, which consists of a number of workstations (K) arranged along a conveyor belt or a similar material handling system, where workpieces are transported between consecutive workstations. A certain number of tasks are performed at each workstation usually following an order of precedence relationship (precedence graph), among other restrictions. The available time for performing the set of tasks assigned to a workstation is called cycle time (C). The sum of all processing times of tasks assigned to a workstation constitutes its workload and must be less than or equal to the cycle time. The difference between the cycle time and the workload is called idle time.

The decision problem of assigning tasks to an ordered sequence of workstations in such a way that one or more objectives are optimised while satisfying some specific constraints is known as Assembly Line Balancing Problem (ALBP). ALBP was first studied by Helgeson et al. (1954). The first mathematical formalisation of ALBP was made by Salveson (1955), who suggested a linear programming solution, focused on the assignment of tasks to workstations. Since these publications, a wide range of heuristics and exact procedures have been proposed to solve ALBP. Many ALBP studies have been carried out to date; some of them are extensive surveys (Ghosh and Gagnon, 1989; Erel and Sarin, 1998; Becker and Scholl, 2006; Boysen et al, 2007, 2008; Battaïa and Dolgui, 2013; Sivasankaran and Shahabudeen, 2014) where ALBPs are classified according to the nature of the problem and their features.

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ALBP can be categorised regarding the similarity of the models assembled on the same line and the shape of the line. Regarding the similarity of models, ALBP can be classified as: single model, mixed-model and multi-model. In single model, only one model is assembled on the line. Each workstation repeatedly performs the same set of tasks. Regarding mixed-model, similar models are assembled on the same line. The main process of the assembled models is quite similar, so that setup time between different models could be reduced sufficiently enough to be ignored. As for multi-model, different models are assembled on the same line. Due to the differences in their production processes, the models are assembled in separate batches to minimise setup times between batches. Figure 1 shows the different types of lines according to the similarity of the models assembled on the line.

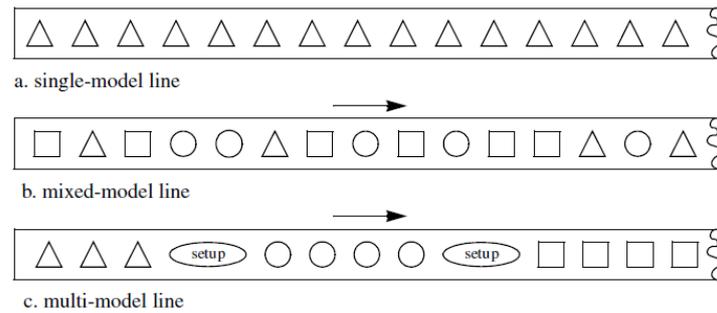


Figure 1. Assembly line for single and mixed/multi model. Reprinted from Becker and Scholl (2006) with permission.

Regarding the shape of the line, ALBP can adopt different types of flow-line production systems depending on the type of model for assembly and its features. In the literature there are different types of line layouts, the most commonly used being straight lines, two-sided lines and U-shaped lines.

- Straight lines (Figure 2a). Single workstations (one-sided workstation) are arranged in a straight line along a conveyor belt.
- Two-sided lines (Figure 2b). Introduced for the first time by Bartholdi (1993), two-sided lines can be operated on both sides of the line (left and right side). Opposite workstations work the same workpiece simultaneously. Some task must be performed on only one of the sides (left or right), while other tasks can be performed on either side of the line.
- U-shaped lines (Figure 2c). Introduced by Miltenburg and Wijngaard (1994), this type of line has the entry and exit located relatively close. Workers located between both legs of the line can walk from one side to the other. Therefore, they can work on both sides in the same cycle.

Figure 2 represents the different line layouts, with the dashed squares representing the workstations, which are manned by an operator, and the number(s) inside the workstation representing the task(s) assigned.

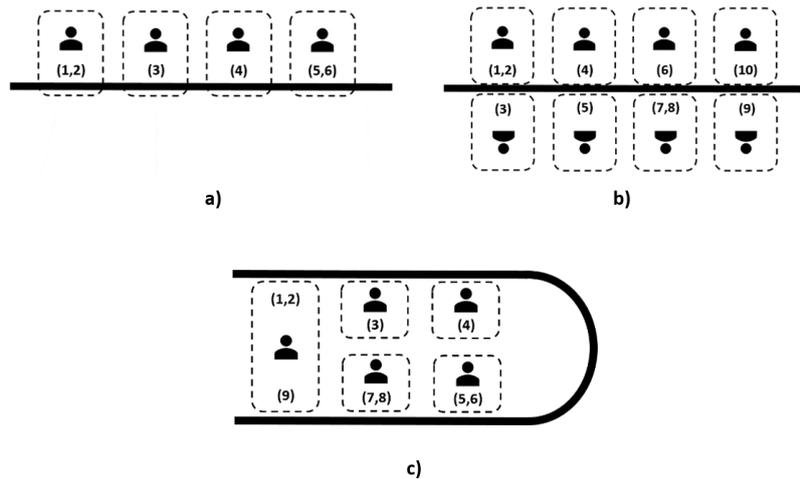


Figure 2. Types of layout: (a) Straight line; (b) Two-sided line; (c) U-shaped line.

The studies on assembly lines can also be classified according to the problem they address. Lusa (2008) classified the studies into four groups:

1. Designing problem, deciding the number of lines and type to be installed.
2. Assigning problem, in single and multi/mixed model assembly lines, the different models are assigned to lines.
3. Balancing problem, assigning tasks among workstations.
4. Evaluating problem, analysis of the performance of the different production systems in order to compare different configurations.

Lusa (2008) did not consider the model sequencing problem. The sequence of models is an important issue that affects the efficiency of the system. Therefore, this factor is considered in this study:

5. Sequencing problem, determining an order of production for the different models assigned to the same assembly line.

On the other hand, Baybars (1986) classified the ALBP into two groups according to their parameters and features: Simple Assembly Line Balancing Problem (SALBP) and General Assembly Line Balancing Problem (GALBP). SALPB is the most common field research and due its simplified nature several articles have been published on it. On the other hand, GALBP introduces other restrictions or factors that appear in real-world problems. Several GALBP studies consider aspects such as parallel tasks (Pinto et al., 1975), parallel workstations (Buxey, 1974), U-shaped lines (Miltenburg and Wijngaard, 1994), alternative subgraph assembly (Capacho et al., 2009), setup times between tasks (Martino and Pastor, 2010), constrained resources (Corominas et al., 2011), hierarchical minimisation of the workloads of the workstations (Pastor et al., 2012), workstations with accessibility windows (Calleja et al., 2013), among others.

The use of more than one assembly line (multiple lines) is also classified within GALBP problems. When the demand for products increases, and the production system does not have enough capacity to deal with this growth, a possible solution is to install multiple lines. According to Lusa (2008), multiples lines provide some advantages over single lines, such as increased flexibility (demand changes), the extension of cycle time(s) and decreased failure sensitivity system (machine breakdowns), among others. On the other hand, the use of multiple lines increases investment cost when compared to single lines. Some researchers (Pinto et al., 1975; Ghosh and Gagnon, 1989; Becker and Scholl, 2006; Lusa, 2008; Battaia and Dolgui, 2013; Sivasankaran and Shahabudeen, 2014) discussed the possibility of using multiples lines on certain occasions.

Multiple lines are two or more identical or different lines, which can be balanced individually or simultaneously. Each assembly line can produce one (single model) or more models (mixed or multi model) and can work with the same or different cycle time. If multiple lines are placed sufficiently close, these lines can be balanced simultaneously. This means that they can share common resources. Commonly, these lines are connected by a multi-line workstation (common workstation between two adjacent lines that performs tasks of both lines). In the multiple lines system, the lines can be located at different positions between them (Figure 3 and Figure 4). According to Gökçen et al. (2010), in a production system, it may not be always possible to locate all lines in parallel. They defined three different types of multi-line workstations. Figure 4 shows these types: (1) parallel connectivity (between line 1 and 2), when two or more lines are located in parallel and they are sufficiently close to each other; (2) consecutive connectivity (between line 2 and 4), with the output of an upstream line (Line 2) being the input of a downstream line (Line 4); (3) perpendicular connectivity (between line 2 and 3), which shows that the output of an upstream line (Line 3) may not always be the only part of a downstream line (Line 2).

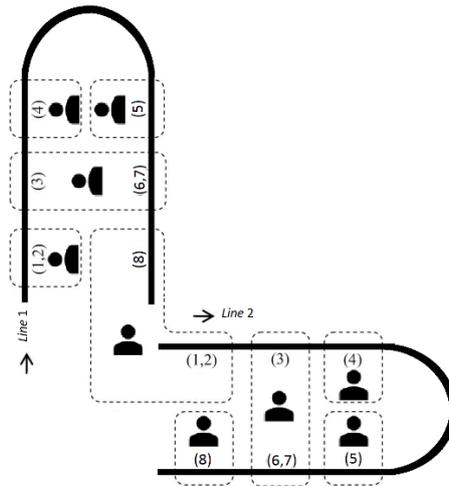


Figure 3. Multiple U-lines connected by a multi-line workstation.

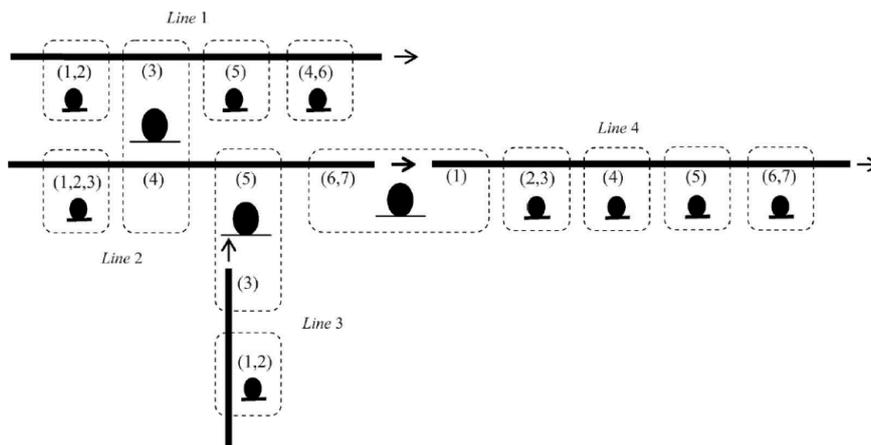


Figure 4. Multiple assembly lines with mixed connectivity. Reprinted from Gökçen et al. (2010) with permission.

Several studies have focused on multiple lines; authors such as Miltenburg (1998) developed a dynamic programming algorithm addressed to the U-line facility (ULF). ULF consists of numerous neighbouring U-lines connected by multi-line workstations, with only one multi-line workstation permitted between two adjacent U-lines (Figure 3). Sparling (1998) introduced the JIT production unit and defined it as a group of several U-lines; when considering travel time, it will be called the NULB-T problem. In the NULB-T problem, multi-line workstations may include tasks of two or more U-lines and each U-line cannot have more than two multi-line workstations. Later, Chiang et al. (2007) introduced the multiple U-line balancing

problem (MULBP); in their study the use of multi-line workstations is not allowed. Gökçen et al. (2010) introduced the Shojinka concept (increase or decrease the number of operators in a productive process when the demand rate changes, by adding workers to some lines and removing them from others) in a multiple straight assembly line balancing (MSLB). Rabbani et al. (2012) presented a modified version of the Multiple U-shape layout (MUSL) to deal with the mixed-model two-sided assembly line balancing (MTALB). The authors study the possibility of one operator being able to work on an opposite workstation in its idle time, helping to accelerate the production rate.

In a multiple lines system, two or more neighbouring lines can also be located in parallel; in this case these lines are called parallel lines (Figure 5). Parallel lines can be balanced individually (Figure 5a) or with multi-line workstations (Figure 5b).

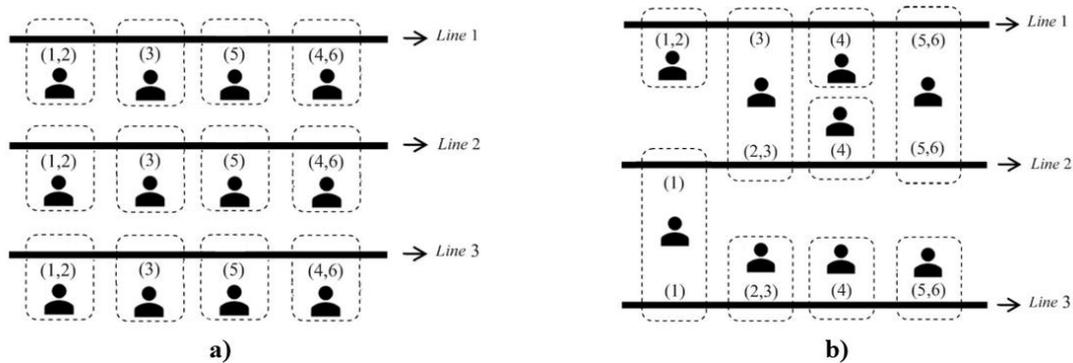


Figure 5. Parallel assembly lines with a) only individual workstations, b) multi-line workstations.

Several studies of the parallel assembly lines with independent balance (Figure 5a) have been presented in the literature. Studies focused on assigning models to several mixed model parallel lines, such as Lehman (1968), which proposed a heuristic procedure with the aim of minimising the total assembly cost; Geoffrion and Graves (1976) presented a quadratic assignment algorithm with the aim of minimising the changeover cost; Ahmadi et al. (1992) developed three different heuristics to minimise the cost associated with assigning models to lines. Other authors such as Wyman and Moberly (1971) evaluated the performance of three different types of parallel line configurations: *Single lines* (two independent single lines), *Dual line* (production line with two identical parallel stations), and *Dual line with expediting* (capability of expediting parts through a station parallel to a failed station). Globerson and Tamir (1980) focused on the impact of human and technological variables on system performance. Chakravarty and Shtub (1988) developed an analytical model linking stochastic system parameters like learning, absenteeism and turnover with productivity. Other authors focused on the design of the assembly systems, deciding the number of lines to be installed. Süer and Dagli (1994) suggested a heuristic procedure to assign several models to a varying number of lines. Pinnoi and Wilhelm (1997) presented a family of hierarchical mathematical models, which incorporate a wide range of features that represent many aspects fundamental to deterministic assembly system design problems. The aim is to minimise the total cost associated with machines, workstations and variable operating. Süer (1998) proposed a three-phase solution methodology to determine how many workers should be assigned to each workstation and how many lines should be installed, with the aim of minimising the total number of workers. Lan (2007) presented a two-phases progressive algorithm to provide the maximum profit.

In the parallel lines system, the lines can be balanced with multi-line workstations; in this case it will from now on be called Parallel Assembly Lines Balancing Problem (PALBP) (Figure 5b) (Gökçen et al., 2006). PALBP can be defined as two or more lines (multiple lines) located in parallel, balanced simultaneously and connected by multi-line workstations (parallel connectivity). In PALBP, the same or different models can be produced on each line with the same or different cycle times.

PALBP is relatively new in the ALBP literature. To the best of our knowledge, only one survey (Lusa, 2008), exists in the literature of multiple or parallel assembly lines. Lusa (2008) compiled the main literature

contributions and provides a comprehensive review until 2008. Moreover, it discusses the advantages and disadvantages of using multiple or parallel assembly lines. Since then, some procedures have been proposed in an attempt to solve PALBP.

The objective of this paper is to provide an up-to-date survey in order to analyse recently published studies about PALBP, to identify their principal strengths, weaknesses and directions for future research. In addition, a classification of the PALBP literature is proposed. The paper is structured as follows. PALBP is defined in Section 2. Section 3 provides a classification scheme for PALBP. In Section 4, a review of the PALBP literature is presented and classified. Section 5 deals with the main advantages and disadvantages. In Section 6, the conclusions and future research directions are presented and discussed.

2. Definition of the PALBP

As previously mentioned, the PALB problem can be defined as two or more lines allocated in parallel, sufficiently close to be balanced simultaneously with multi-line workstations and share common resources (e.g. operators). Each line may produce only one model (single line), similar models (mixed-model line) or different models (multi-model line).

Özcan et al. (2010a) enumerate the main advantages of PALBP over single lines: (1) it can reduce the failure sensitivity in case of line breakdown, allowing production of similar or different models on adjacent lines; (2) it can reduce the idle time and increase the efficiency of the assembly lines; (3) it can allow for production with a different cycle time for each of the lines; (4) it can improve visibility and communication skills between operators; and (5) it can reduce operator requirements.

The following assumptions are commonly considered in the PALBP studies (Gökçen et al., 2006; Özcan et al., 2009; Baykasoğlu et al., 2009; among others):

- I. Two or more lines located in parallel to each other.
- II. Task times of each model are known.
- III. Precedence diagram of each model is known.
- IV. Each task is assigned only to one workstation.

Figure 6 represents a schematic view of the PALBP lines, showing the different parts that comprise it such as regular/multi-line workstations, workplaces and stages. The workstation is a physical space used to delimit a work zone, a workstation can cover one (regular workstation) or two workplaces (multi-line workstation). A workplace is the specific zone where one or more operators perform a set of tasks. The stages are non-physical divisions that cover a number of workstations placed in the same division. The stages are used to represent the total length of the line. For example, Figure 6 consists of 14 workplaces, 11 workstations (therefore, 11 operators) and 5 stages. The red dashes are used to show the stage divisions e.g. the Stage 1 covers workstations 1 and 2. Moreover, the example of Figure 6 contains 3 multi-line workstations (workstations 2, 3 and 10).

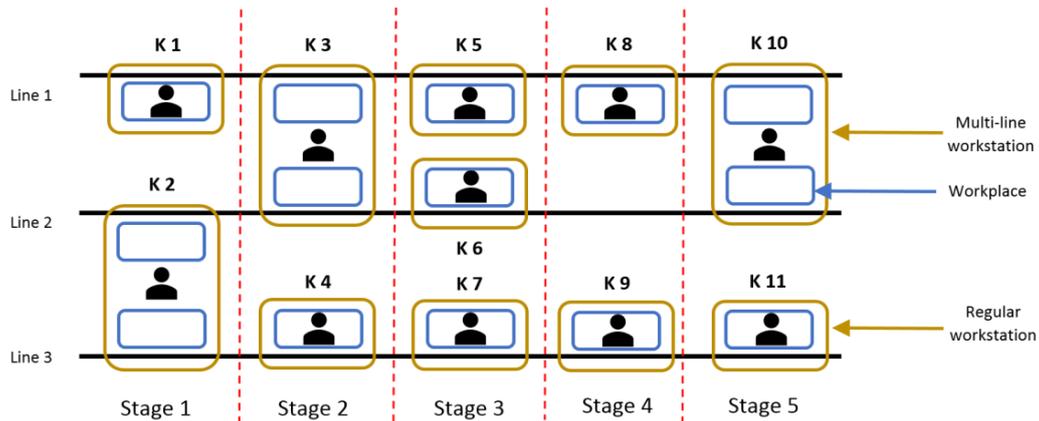


Figure 6. Schematic view of PALBP lines.

3. A classification scheme for the PALBP

In the following, a scheme is presented for classifying the PALBP literature. This scheme is used to make different summary tables (in section 4), where PALBP studies will be categorised. Different attributes and features of the problems are presented below, to provide an understanding of the main contributions and approach solutions suggested. As Graham et al. (1979), Boysen et al. (2007) and Allahverdi (2015) did, in this study a notation $[\alpha|\beta|\gamma]$ is used to classify the PALBP literature into three fields, based on the type of problem they address (α), its features (characteristics and restrictions, β) and the objective to be optimised (γ).

Additional problem attributes and resolution methods will also be introduced in this section and utilised to make the different summary tables more understandable, presented in section 4.1, 4.2 and 4.3.

3.1 Type of problem (α)

In this work, the type of problem encompasses different aspects such as line layout, similarity of models and the nature of the problem.

Assembly lines are the most common production system for making a product, but in industry, we can distinguish other types of systems, like disassembling lines (DL). DL are the most important and main step of product recovery activities (Hezer and Kara, 2015). Moreover other production systems are composed for both assembly and disassembly lines (Mete et al., 2017). We can distinguish between three different types of production lines:

- Assembly lines: \emptyset .
- Disassembly lines: DL.
- Mixed production system, Assembly and Disassembly lines: ADL.

PALBP can adopt different combinations between line layout and models assembled. A classification is proposed according to different studies presented in the PALBP literature.

- *Parallel Lines - Straight lines (PS) or parallel straight lines*, are two or more straight lines placed in parallel and balanced with the possibility of using multi-line workstations.
- *Parallel Lines - Two-sided (PT) or parallel two-sided lines*, are two or more two-sided lines placed in parallel and balanced with the possibility of using multi-line workstations.

- *Parallel Lines - U-shaped (PU) or parallel U-shaped lines*, are two or more U-shaped lines placed in parallel and balanced with the possibility of using multi-line workstations.

In the three cases PS, PT and PU, the lines can produce any type of the different models (single model (*SM*), mixed-model (*MM*) and multi-model (*MuM*)). Figure 7 shows the resultant categories.

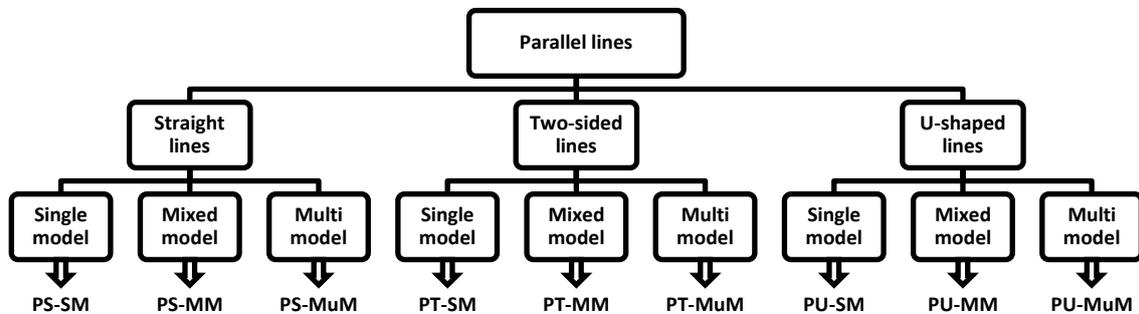


Figure 7. Classification of the PALBP.

The notation used to identify the type of production line (assembly, disassembly or both) and the line layout with the production models (PS, PT and PU), can be represented as PS-SM for Parallel straight assembly lines single model, PS-DL-SM for Parallel straight disassembly lines single model or PS-ADL-SM for Parallel straight assembly/disassembly lines single model.

Finally, PALB problems can be classified in 4 different groups with regard to the nature of the problem:

- Designing (De).
- Assigning (Ag).
- Balancing (Ba).
- Sequencing (Se).

3.2 Problem features (β)

Problem features are related with the restrictions and characteristics of different elements that form the assembly line, such as tasks, cycle time, workstations, resources, operators and line characteristics.

3.2.1 Task related (Task):

- Task time: Depending on the nature of the tasks, this can be divided into two groups:
 - *Deterministic* task time (D), the processing times are considered to be fixed and deterministic operation times.
 - *Stochastic* task time (St), assumes that the processing times follow a known (or even unknown/partially known) distribution function.
- Task restrictions:
 - \emptyset : no task assignment restrictions are considered.
 - T1: a task has to be assigned to a specific workstation.
 - T2: *synchronism*, some tasks required to be performed simultaneously with another task.
 - T3: *positive zoning*, a set of linked tasks must be assigned to the same workstation.
 - T4: *negative zoning*, a set of incompatible tasks must not be assigned to the same workstation.

- T5: distance (minimum or maximum) needed between tasks, the distance can be expressed in terms of time or space.
- T6: some tasks can be performed only on either the left/right sided of the line.
- Task time increments:
 - \emptyset : no task time increments are considered.
 - Ts: *setup*, set of activities required (machine configuration, tool change, cleaning, etc.) before/after performing a task.
 - Tw: walking distance to change of line between two neighbouring lines or return to the beginning of the workstation at the end of the cycle time.
- Task process:
 - \emptyset : the tasks are performed by human operators.
 - Tr: the tasks are performed by robots.

3.2.2 *Cycle time related (C):*

- Cycle time:
 - 1: the parallel lines have the same cycle time.
 - 2: the parallel lines can have different cycle times.

3.2.3 *Workstation related (K):*

- Workstation equipment:
 - \emptyset : workstations are fully equipped.
 - We: workstations with different level of equipment.
- Workstation restrictions:
 - \emptyset : no workstation restrictions are considered.
 - Wo: more than one operator is allowed per workstation.
 - Ws: limited space (length of stations, space for tools or materials, etc.).

3.2.4 *Resources related (Res):*

- Resource restrictions:
 - \emptyset : no resource restriction.
 - R1: some tasks require a specific equipment or assistant.
 - R2: some task times can be reduced by the use of specific equipment or assistant.
 - R3: resources (equipment and/or assistant) are limited.

3.2.5 *Operator related (Op):*

- Operator restrictions:
 - \emptyset : no operator restrictions are considered.
 - O1: operators assignment to perform tasks according to their different skill levels.

3.2.6 *Line characteristics (Line):*

- Flow-line production:

- \emptyset : all the assembly lines have the same production flow orientation.
- L: the assembly lines have different production flow orientation.

3.2.7 Additional features

- Observation: additional features of the problem.

3.3 Objective (γ)

The objective functions that have been dealt in the PALBP literature are:

- Minimising the number of workstations (K), is the objective most frequently to be optimised, commonly subject to a given maximum cycle time.
- Minimising the cycle time (C) or maximising the production rate for a given number of workstations.
- Maximising the line efficiency (E), is equivalent to minimising the product of number of the workstations and cycle time.
- Minimising the cost (CO), this objective covers costs related to various elements of assembly lines such as workstation equipment (machinery, tools), operators (wages) and failure time (repair, maintenance).
- Minimising the smoothness index (S) or other variants: the objective is to reduce the differences of the workstation workloads.
- Minimising the number of stages (total length line) (LL): the objective is to compact the line and thus, save space.
- Minimising the number of tasks that are above a predetermined value assigned to each workstation (T), due to physical, technological or other reasons.
- Minimising the skill variation within workstations (SV).
- Minimising the walking time (W): reducing the time of walks between parallel lines.

3.4 Problem attributes

There is a group of features that define and condition the difficulty of the problem to be solved. These features can be *fixed* (given for the assumptions of the problem) or can be values to be determined. This study considers the following characteristics:

- Number of lines (Line): the number of lines can be *fixed* (F) or *to be determined* (TBD).
- Number of workstations (K): the number of workstations can be *fixed* (F) or *to be determined* (TBD).
- Number of operators (O): the number of operators can be *fixed* (F) or *to be determined* (TBD).
- Number of stages (LL): the number of stages (or length line) can be *fixed* (F) or *to be determined* (TBD).
- Cycle time (C): can be *fixed* (F) or *to be determined* (TBD).

3.5 Resolution method abbreviations

Table 1 list the different methods that have been used to solve the problems presented in the PALBP literature. For each one, its abbreviature is shown in the following table.

Table 1. Approaches and exact procedures abbreviations.

Solution approach	Abbreviation
<i>Ant Colony Optimization</i>	ACO
<i>Artificial Bee Colony</i>	ABC
<i>Bee Algorithm</i>	BA
<i>Beam Search</i>	BS
<i>Binary Linear Programming</i>	BLP
<i>Biogeographic-based optimisation</i>	BBO
<i>Branch-and-Bound</i>	B&B
<i>Dynamic Programming</i>	DP
<i>Genetic Algorithm</i>	GA
<i>Goal Programming</i>	GP
<i>Heuristic</i>	HEUR
<i>Mixed Integer Linear Programming</i>	MILP
<i>Mixed Integer Nonlinear Programming</i>	MINLP
<i>Network model</i>	NM
<i>Scatter Search</i>	SS
<i>Simulated Annealing</i>	SA
<i>Tabu Search</i>	TS

4. Review of the PALBP

In the following subsections, the PALB literature will be introduced according to the classification proposed in Figure 7. Moreover, in each subsection a summary table is presented using the notation proposed in Section 3. Finally, Table 8 groups all the published studies in alphabetical order.

Multi-model (MuM) lines are not contemplated in the PALBP literature yet; therefore they are not considered in the following subsections.

4.1 Parallel Straight lines (PS)

Parallel straight lines are the most common PALB layout in the literature (for instance, Figure 6). The layout is characterised by two or more straight lines located in parallel to each other.

Using the classification scheme provided previously in Section 3, Table 2 and Table 3 (shown in Section 4.1.1 and 4.1.2, respectively) list chronologically the studies presented on PS.

4.1.1 Parallel Straight Lines – Single-model (PS-SM)

PALBP was introduced for the first time in the literature by Gökçen et al. (2006). The authors proposed a binary linear programming (BLP) model and two heuristic procedures (active and passive case procedure) for the problem [PS-SM,Ag-Ba|D,2|K] with two lines. The passive case procedure is used for the problem of two different parallel assembly lines that produced the same model with the same cycle time (C). The authors suggest the following steps: 1) balancing the lines using any method for SALBP-1; 2) computing the idle time for each workstation; and 3) if there are two opposite workstations with an idle time, each one equal or greater than $C/2$, these two regular workstations should be transformed into one multi-line workstation. The active case procedure is used for the problems of two parallel assembly lines, each producing different or similar models with the same cycle time. This method proposed by the authors is similar to COMSOAL (Arcus, 1965). In case of having different cycle times, the authors proposed a least

common multiple (LCM) approach to obtain a common cycle time. This approach follows the next steps: 1) finding the least common multiple of the cycle times; 2) obtaining D1 and D2 values by dividing both cycle times by the least common multiple; 3) multiplying the task times of each precedence graph with D1 and D2; and 4) using the least common multiple as cycle time. If D1 and D2 are different, each line will produce a different number of units per cycle time, in batches with the amounts of D1 and D2. In an active case procedure, if more than two lines are considered, the assignment of models per line is considered in the procedure. Moreover, in both cases (passive case and active case) it would be possible to add the operator walking time (T_w). In the process of assigning tasks to workstations, T_w has to be taken into account in the total workstation time. Although considered in both procedures, T_w is not considered in the computational experiment.

Benzer et al. (2007) proposed a network model based on the shortest-route model developed by Gutjahr and Nemhauser (1964), addressing the problem of [PS-SM,Ba|D,1|K]. Only a numerical example is given to illustrate the proposed procedure.

A simulated annealing (SA) heuristic approach was developed by Çerçioğlu et al. (2009) to solve the problem [PS-SM,Ba|D,2|K]. SA have been developed to solve the same problem as Gökçen et al. (2006). In the case of having lines with different cycle times, LCM is used to obtain a common cycle time.

Özcan et al. (2009) presented the first multi objective PALBP study in the literature. The authors developed a Tabu Search (TS) algorithm to solve the problem [PS-SM,Ba|D,2|K,S] with two simultaneous objectives: (1) minimising the number of workstations (K) and (2) minimising the smoothness index (S). In order to combine these performance criteria into a single function, minimum deviation method (MDM) is used. MDM finds the best compromise solution which minimises the sum the of individual objective's fractional deviations. If cycle times are different, the following procedure is applied to obtain a common cycle time: 1) a normalised task operation time should be obtained by dividing the task times of line h by the cycle time of line h ; and 2) the cycle time should be defined as $C=1$ for both lines.

A BLP model and a Branch-and-Bound procedure were proposed by Scholl and Boysen (2009) for the problem [PS-SM,Ag-Ba|D,1|K]. The authors showed that multi-line workstations have the potential to increase working efficiency by reducing the number workstations, but this might come at the cost of additional requirements in space, and empty workstations might be necessary. This is overcome by additional second that guarantees that each workstation is installed as early as possible, which favours compacting the line layout. The product-line-assignment decision is considered in the mathematical model and the exact solution procedure. Moreover, the walking time between lines can be considered in the BLP, but is not considered in the computational experiment.

Baykasoğlu et al. (2009) proposed an Ant Colony Optimisation (ACO) based algorithm for the problem [PS-SM,Ba|D,1|K,S] and an Scatter Search (SS) based heuristic algorithm was developed by Guo and Tang (2009) for the problem [PS-SM,Ba|D,1|K].

Kara et al. (2010) presented a two goal programming approach addressed to the problem [PS-SM,Ba|D,2|K,C,T] with fuzzy objectives. Goal programming (GP) and Fuzzy Goal Programming (FGP) were developed with the aim of minimising three conflicting objectives: the number of workstations (K), the cycle time (C) and the number of tasks above a predetermined value that are assigned to each workstation (T). The approaches proposed providing the decision makers with flexibility in balancing the lines based on their decision environment and preferred priorities. Constraints as number of workstations, cycle time and of tasks above a predetermined value that are assigned to each workstation and act as soft constraints in the objective function. A FGP called Binary Fuzzy Goal Programming (BFGP), presented by Chang (2007), is adopted to balance parallel assembly lines with fuzzy objectives. The parallel lines can work with different cycle times, in which case the LCM procedure is used to obtain a common cycle time. Only a numerical instance problem is solved to illustrate the proposed GP and BFGP approaches

Özbakir et al. (2011) presented a meta-heuristic multiple-Colony Ant Algorithm (mc-ACO) as an extension of the procedure presented by Baykasoğlu et al. (2009) addressed to the problem [PS-SM,Ba|D,1|K,S]. The mc-ACO algorithm is based on the cooperation and exchange information of the different ant colonies to achieve a greater field of search and to be able to find better solutions. The problem assumes that number of lines is equal to number of models.

Multiple-colony ACO algorithm (mc-ACO) developed by Özbakir et al. (2011) was modified and proposed by Baykasoğlu et al. (2012) to solve the problem [PS-SM,Ba|St,1|K] with fuzzy task time and fuzzy cycle time (i.e. the task time variability, providing these data with uncertain values). The problem assumes that the number of lines is equal to the number of models. Triangular Fuzzy Numbers (TFN) is used to represent fuzziness task times and cycle times.

Grangeon and Norre (2012) proposed a combination of a metaheuristic based on SA and a Bin-packing heuristic proposed by Gourgand et al. (2007) to solve the problem [PS-SM,Ba|D,1|K].

Kara and Atasagun (2013) introduced a new problem called PALBP with Resource Dependent Task Times. The authors address the problem [PS-SM,Ba|D,2,R1,R2,R3,We,Wo|CO]. They stated that the actual time required to process a task at a workstation depends on the processing alternative (set of workers, assistants and equipment) assigned to the workstation. A worker may need assistance to perform tasks on some parts or the assistance of another worker can reduce the processing time of a task. The authors adapt the resources dependent assembly line balancing (RDALB) presented by Kara et al. (2011) to PALBP. A binary linear programming (BLP) model was developed, with the objective of minimising the total cost associated with the workstation (assistant assignment and equipment allocation). The problem assumes that the parallel lines may have different cycle times, in which case the LCM approach can be used. Moreover, the number of operators is enough to operate the workstations, but the resources (equipment and assistants) are limited.

Araújo et al. (2015) presented a new problem motivated by the context found in sheltered work centres, where disabled workers perform tasks at different rates. This paper is focused on balancing two or more Assembly Line Worker Assignment and Balancing (ALWAB), the problem arising is a PABLP with Worker Assignment. ALWABP defines worker-dependent processing times which allow the diversity of workers to be taken into account and can, therefore, be useful in other environments. The main idea is to generate a set of operators that can be assigned together to an assembly line and can execute all tasks assigned. A mixed-integer linear programming (MILP) model and two heuristics, Tabu Search (TS) algorithm and Biased Random-Key Genetic Algorithm (BRKGA) were proposed for the problem [PS-SM,Ba|D,T3,2,O1|C].

Hezer and Kara (2015) presented a new problem focused on product recovery, activities performed for the recovery of post-consumer products. The system focused on these activities is called Disassembly Line Balancing Problem (DLBP). A network model (NM) based on Shortest Route Model (SRM) (Gutjahr and Nemhauser, 1964; Benzer et al., 2007) is developed to solve the problem [PS-DL-SM,Ba|D,1|K]. The problem assume that the number of lines is equal to the number of models.

Çil et al. (2017) first introduced, in the ALBP literature, the combination between parallel lines with multi-line workstations and robotic assembly lines (RAL). In the RALB problem, the robot must be considered when tasks are assigned to workstations, due to the possibility of having different types of robots at the assembly facility, with different abilities and efficiencies in performing the same task. The authors proposed mixed integer linear programming (MILP) for small size instances and developed three meta-heuristics (iterative beam search (IBS), best search method IBS (BIBS) and cutting BIBS (CBIBS)) based on the Beam Search (BS) approach, for the problem [PS-SM,Ba|D,Tr,1,O1|C].

Mete et al. (2017) proposed a PALBP composed for assembly and disassembly lines, on which products and parts move reversely. They developed an heuristic approach based on ACO algorithm to solve the problem [PS-ADL-SM,Ba|D,1,L|K]. The ACO proposed used a new heuristic priority rule based on minimum task processing time as task selection strategy for disassembly lines. Moreover a transformed

AND/OR graph (TAOG) presented by Koç et al. (2009) was used as precedence graph for disassembly lines.

Özcan (2018) proposed a chance constraint, piecewise, mixed integer linear programming (CPMIP) and a Tabu search (TS) algorithm addressed to the problem [PS-SM,Ba|St,2|K]. CPMIP is a MILP adapted to stochastic data with some modifications; chance constraint is used to ensure that the probability of a workstation's workload is less than the cycle time and is within a pre-determined confidence level $1-\alpha$; and piecewise being used to build a function that fits a non-linear function. The number of assembly lines is equal to the number of models. If parallel lines have different cycle times, LCM approach is used to obtain a common cycle time.

Table 2. Classification of parallel straight lines – single model

Author	Type Problem	Problem attributes					Problem features						Objective								Solution approach	Observations		
		Line	K	C	O	LL	Task	C	K	Res	O	Line	K	C	E	CO	S	LL	T	SV			W	
Gökçen et al. (2006)	Ag-Ba	F	TBD	F	TBD	TBD	D	2					•										BLP and HEUR	
Benzer et al. (2007)	Ba	F	TBD	F	TBD	TBD	D	1					•										NM	Only illustrated by an example
Çerçioğlu et al. (2009)	Ba	F	TBD	F	TBD	TBD	D	1					•										SA	
Özcan et al. (2009)	Ba	F	TBD	F	TBD	TBD	D	2					•				•						TS	
Scholl and Boysen (2009)	Ag-Ba	F	TBD	F	TBD	TBD	D	1					•										BLP and B&B	
Baykasoğlu et al. (2009)	Ba	F	TBD	F	TBD	TBD	D	1					•				•						ACO	
Guo and Tang (2009)	Ba	F	TBD	F	TBD	TBD	D	1					•										SS	
Kara et al. (2010)	Ba	F	TBD	TBD	TBD	TBD	D	2					•	•						•			GP and Binary Fuzzy GP	Precise and fuzzy goals. Soft constraints.
Özbakir et al. (2011)	Ba	F	TBD	F	TBD	TBD	D	1					•				•						ACO	
Baykasoğlu et al. (2012)	Ba	F	TBD	F	TBD	TBD	St	1					•										ACO	BLP to model the problem. Fuzzy cycle and task times
Grangeon and Norre (2012)	Ba	F	TBD	F	TBD	TBD	D	1					•										SA and HEUR	
Kara and Atasagun (2013)	Ba	F	TBD	F	TBD	TBD	D	2	We, Wo	R1,R2, R3						•							BLP	Resource dependent task time
Araújo et al. (2015)	Ba	F	F	TBD	F	F	D, T3	2				O1		•									MILP, TS and Biased random-key GA	
Hezer and Kara (2015)	DL, Ba	F	TBD	F	TBD	TBD	D	1					•										NM	
Çil et al. (2017)	Ba	F	F	TBD	F	F	D, Tr	1				O1		•									MILP and BS	

Table 2 (*continuation*). Classification of parallel straight lines – single model

Author	Type Problem	Problem attributes					Problem features					Objective										Solution approach	Observations	
		Line	K	C	O	LL	Task	C	K	Res	O	Line	K	C	E	CO	S	LL	T	SV	W			
Mete et al. (2017)	ADL, Ba	F	TBD	F	TBD	TBD	D	1				L	•										ACO	
Özcan (2018)	Ba	F	TBD	F	TBD	TBD	St	2					•										TS	MILP to model the problem

4.1.2 *Parallel Straight Lines - Mixed-model (PS-MM)*

Esmailian et al. (2009) first introduced the mixed-model problem in the PALBP literature. They developed a single-pass heuristic to solve the problem [PS-MM,Ba|D,2|C].

Özcan et al. (2010a) developed a simulated annealing (SA) approach to solve the problem [PS-MM,Ba-Se|D,2|K,S]. The assignation of products on the lines is pre-determined and each line has its own set of models. The minimum part of set (MPS) principle proposed by Bard et al. (1992) is used to obtain a mix of production for each line, with the model sequence for each line randomly generated in the proposed approach. The parallel lines can have the same or different cycle times; for both cases a normalised cycle time has to be calculated, as in Özcan et al. (2009).

Esmailian et al. (2011) presented a binary linear programming and a Tabu Search (TS) approach to solve the [PS-MM,Ba|D,2|C].

Esmailian et al. (2015) presented a mathematical model based on the Dual-Resource Constrained (DRC), DRC considering the limitations of both machinery and manpower at the same time. The problem [PS-MM,Ba|D,2,O1|K,CO] assumes that only two parallel lines are used. The workers are classified according to their skill level and are randomly selected for assignment to the appropriate workstation based on their productivity, in order to save the cost of direct labour. The cycle time of the system is assumed as the maximum cycle time of all the models.

Chutima and Yothaboriban (2017) focused on covering different gaps in the literature, such as skill relatedness of tasks assigned to workstations. This means that each worker has a primary skill and a secondary skill in which they are less proficient; the idea is to allocate the right worker (skill) to the right job (workstation). The authors proposed an evolutionary algorithm Biogeographic-based optimisation (BBO) to solve the problem [PS-MM,Ba-Se|D,2,O1|K,S,LL,SV]. A fuzzy logic controlled (FCL) is integrated with BBO, called fuzzy adaptive BBO (F-BBO); FCL allows the dynamic adjustment of the BBO parameters. Three objective functions are evaluated hierarchically for optimisation: 1) To minimise the number of workstations (K); 2) Minimise the number of stages (LL); 3) The third objective comprises two sub-objectives: minimising the workload variation between workstations (S) and minimise the skill variations within workstations (SV). A ranking scheme based on Pareto is employed to evaluate the solutions obtained by the third objective. In this problem, parallel lines may have different cycle times, in which case the LCM approach is used to obtain a common cycle time. Mix of production is obtained by using MPS principle.

Table 3. Classification of parallel straight line – mixed model

Author	Type Problem	Problem attributes					Problem features					Objective								Solution approach	Observations			
		Line	K	C	O	LL	Task	C	K	Res	O	Line	K	C	E	CO	S	LL	T			SV	W	
Esmacilian et al. (2009)	Ba	F	TBD	TBD	TBD	TBD	D	2						•									HEUR	
Özcan et al. (2010a)	Ba-Se	F	TBD	F	TBD	TBD	D	2					•				•						SA	
Esmacilian et al. (2011)	Ba	F	TBD	TBD	TBD	TBD	D	2						•									TS	BLP to model the problem
Esmacilian et al. (2015)	Ba	F	TBD	F	TBD	TBD	D	2			O1		•			•							BLP	Only 2 instances are solved
Chutiima and Yothaboriban (2017)	Ba-Se	F	TBD	F	TBD	TBD	D	2			O1		•				•	•		•			BBO	BLP to model the problem

4.2 Parallel Two-sided lines (PT)

The two-sided assembly line (TAL) uses both sides of the line to enhance the assembly performance of a large production system such as cars, buses and trucks. In two-sided lines, some tasks have to be performed on one side of the line (left (L) or right (R)), but other tasks could be performed at either (E) side of the line. According to Özcan et al. (2010b) the main advantages of two-side lines over one-sided lines are: (1) the assembly line can be shorter than one-sided assembly line; (2) it can reduce material handling costs, worker movement, set up time and the amount of throughput time; and (3) it can also reduce the cost of tools and fixtures. Parallel two-sided lines are two or more two-sided lines arranged parallel to each other and balanced with multi-line workstations. Figure 8 shows an example of parallel two-sided lines composed of 1 stage that covers 2 regular workstations (workstations 1 and 3), 1 multi-line workstation (workstation 2) and 3 operators.

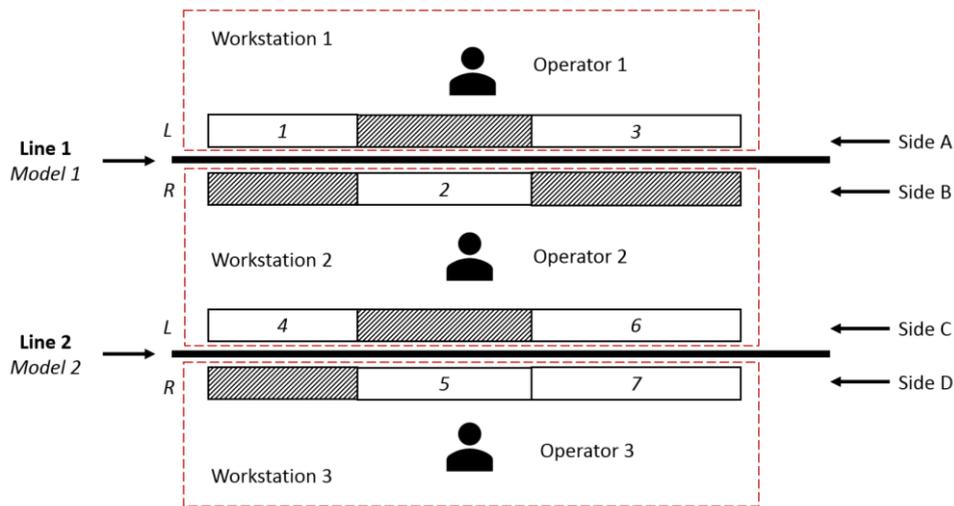


Figure 8. Parallel two-sided lines.

Table 4 and Table 5 (shown in Section 4.2.1 and 4.2.2, respectively) chronologically list the studies referring to PT.

4.2.1 Parallel Two-sided lines – Single-model (PT-SM)

Özcan et al. (2010b) presented the first study addressed to simultaneously balancing more than one two-sided assembly line located in parallel to each other. The authors introduced and characterised the problem [PT-SM,Ba|D,T6,2|K] and developed a Tabu Search (TS) algorithm to solve the problem. Each two-sided assembly line may have different cycle times, in this case the LCM approach is used to obtain a common cycle time.

An ant colony optimisation (ACO) based approach was developed by Kucukkoc et al. (2013) to attempt to solve the problem [PT-SM,Ba|D,T6,2|K,LL]. The ACO algorithm proposed in this paper has a new pheromone releasing strategy, with two types of pheromone release strategy being used to help the ants find solutions more efficiently. A weighting factor allows weights of the total length of the line (LL) in the objective function with regard to the number of workstations (K). The number of lines is equal to the number of models (two in this study) and the assignation of models is pre-determined. LCM is used if the cycle times are not the same for each line. The proposed procedure has not been compared with other resolution processes, but two instances were solved to illustrate the proposed ACO heuristic.

Kucukkoc and Zhang (2013) presented a Genetic Algorithm (GA) approach addressed to the problem [PT-SM,Ba|D,T6,2|K]. The number of lines (two in this study) is equal to the number of models and the

assignment of models is given by the problem. Parallel lines may have different cycle times, in that case LCM is used. A numerical example was shown to illustrate the functioning of the proposed procedure.

Ađpak and Zolfaghari (2015) developed a mixed integer linear programming (MILP) model focused on 5 problems with different objective functions and with the possibility of adding several restrictions. The authors classified the problem and its extensions as: Type I/LL, for a given cycle time, minimising the number of stages (line length) [PT-SM,Ba|D,T6,2|LL]; Type I/K, for a given cycle time, minimising the number of workstations [PT-SM,Ba|D,T6,2|K]; Type II-K, for a given number of workstations, minimising cycle time [PT-SM,Ba|D,T6,2|C]; Type II-LL, for a given number of stages, minimising cycle time [PT-SM,Ba|D,T6,2|C]; minimising the total cost [PT-SM,Ba|D,T6,2|CO] which includes workstation, stages and labour costs. Moreover, several assignment restrictions such as workstation (e.g. assigning a task to specific workstation) (T1), synchronisation (moving or performing tasks) (T2), positive and negative zoning (T3 and T4), distance (between tasks) (T5) and resource (space area or length) (Ws), are presented and can be used for the different problems proposed.

Kucukkoc and Zhang (2015d) first introduced the *type-E* problem in the parallel two-sided literature. A mixed integer linear programming (MILP) model was proposed for the formal description of the problem [PT-SM,Ba|D,T6,2|E] and an ant colony optimisation (ACO) based approach enhanced by three well-known heuristics (COMSOAL, Ranked Positional Method and Shortest Processing Time) was developed to solve it. Response Surface Methodology (RSM) proposed by Box and Wilson (1951) is used for calibrating ACO parameters. The problem assume that the number of lines is equal to the number of models.

Kucukkoc and Zhang (2015a) developed a Genetic Algorithm (GA) based approach to solve the problem [PT-SM,Ba|D,T3,T4,T6,2|K], and a mixed integer nonlinear programming (MINLP) model was developed to present the problem. The current study is the continuation of the work presented by Kucukkoc and Zhang (2013). In this problem each assembly line may have a different cycle time, in which case LCM is used to obtain a common cycle time. In addition, the number of lines is equal to the number of models.

Walking time (in multi-line workstations) was introduced to PT-SM by Tapkan et al. (2016), who modelled the problem as a mixed integer nonlinear programming (MINLP) model. Due to its high complexity, Bee Algorithm (BA) and Artificial Bee Colony (ABC) were developed to solve the problem [PT-SM,Ba|D,T6,Tw,2|K,S,W]. The LCM approach is used in case of parallel lines with different cycle times.

Table 4. Classification of parallel Two-sided lines – single model

Author	Type Problem	Problem attributes					Problem features						Objective								Solution approach	Observations	
		Line	K	C	O	LL	Task	C	K	Res	O	Line	K	C	E	CO	S	LL	T	SV			W
Özcan et al. (2010b)	Ba	F	TBD	F	TBD	TBD	D, T6	2					•									TS	
Kucukkoc et al. (2013)	Ba	F	TBD	F	TBD	TBD	D, T6	2					•					•				ACO	
Kucukkoc and Zhang (2013)	Ba	F	TBD	F	TBD	TBD	D, T6	2					•									GA	
Ağpak and Zolfaghari (2015)	Ba	F	TBD/ F	TBD/ F	TBD	TBD/ F	D, T1, T2, T3, T4, T5, T6	2	Ws				•	•		•		•				MILP	Different mathematical models
Kucukkoc and Zhang (2015d)	Ba	F	TBD	TBD	TBD	TBD	D, T6	2							•							ACO	MILP to model the problem
Kucukkoc and Zhang (2015a)	Ba	F	TBD	F	TBD	TBD	D, T3, T4, T6	2					•									GA	MINLP to model the problem
Tapkan et al. (2016)	Ba	F	TBD	F	TBD	TBD	D, T6, Tw	2					•								•	BA and ABC	MINLP to model the problem

4.2.2 *Parallel Two-sided lines – Mixed-model (PT-MM)*

Zhang and Kucukkoc (2013) introduced a mixed-model problem in the parallel two-sided lines, with PT-MM combining the benefits of *parallel lines* and *two-sided lines* with the *mixed-model* flexibility. The author's aim was not to develop a method of solving [PT-MM,Ba|], but of introducing the problem. They give an example to illustrate the problem.

Following the previous study, Kucukkoc and Zhang (2014c) developed an Agent Based Ant Colony Optimisation and Sequencing (ABACO/S) algorithm framework to deal with the problem [PT-MM,Ba-Se|D,T3,T6,2|K,S,LL]. A multi-objective model is considered with the aim of minimising the number of workstations, minimising the smoothness index and minimising the length of the line. The inclusion of weighting factors allows the significance levels of objectives to be decided. All the possible model sequences based on Minimum part set (MPS) are generated in the ABACO/S procedure. The LCM approach is used in the case of considering assembly lines with different cycle times. An instance problem was solved to illustrate the proposed ABACO/S procedure, but the approach was not tested to analyse its performance.

Kucukkoc and Zhang (2014a) presented a modified version of the ABACO/S algorithm proposed by Kucukkoc and Zhang (2014c). In this paper, unlike Kucukkoc and Zhang (2014c), the model sequence and smoothness index are not taken into account in the problem [PT-MM,Ba|D,T3,T6,2|K,LL]. The ABACO algorithm presented is enhanced by ten heuristics (COMSOAL, ranked positional weight method (RPWM), reverse ranked positional weight method (RRPWM), longest processing time (LPT), shortest processing time (SPT), smallest task number (STN), maximum number of predecessors (MNP), least number of predecessors (LNP), maximum number of successors (MNS), least number of successors (LNS)); these heuristics are randomly selected by ants to obtain a balanced solution. The objective functions K and LL can be weighted by the user according to their importance. The cycle time of each line may be different, in which case LCM is used.

Kucukkoc and Zhang (2014b) presented the continuation of Kucukkoc and Zhang (2014c) and (2014a). In this study, as in Kucukkoc and Zhang (2014a), PT-MM with model sequencing is modelled as a mixed integer linear programming (MILP) model and the ABACO/S algorithm is enhanced by ten heuristics. As in Kucukkoc and Zhang (2014c), the model sequence is considered in the procedure. The problem [PT-MM,Ba-Se|D,T3,T4,T6,2|K,S,LL] uses weighting factors to define the weight of each objective. The ABACO/S algorithm presented in this study can use two different sequencing models: (1) combinatorial model sequencing and (2) random model sequencing. In Combinatorial model sequencing, the algorithm tries all possible model sequences. In Random model sequencing, the algorithm tries a defined number of random model sequences. If parallel lines have different cycle times, the LCM approach is used to obtain a common cycle time.

Kucukkoc and Zhang (2016a) presented a new hybrid agent-based ant colony optimization-genetic algorithm (ABACO/S-GA) approach to solve the problem [PT-MM,Ba-Se|D,T3,T6,2|K,LL]. GA is integrated with ABACO/S to generate different model sequences. In addition, to provide heuristic information and increase the local search capacity of the algorithm, ten heuristics are available to be selected by each ant, as was proposed in Kucukkoc and Zhang (2014a). The main objective is to minimise the number of workstations (K) and the total line length (LL); these objectives can be weighted by factors. Parallel assembly lines may have different cycle times, so LCM approach is used to obtain a common cycle time.

A flexible ABACO algorithm addressed to the problem [PT-MM,Ba|D,T3,T6,2|K,LL] was proposed by Kucukkoc and Zhang (2016b); they modified the ABACO/S algorithm proposed by Kucukkoc and Zhang (2014a) to developed a flexible ABACO algorithm, which builds flexible balancing solutions suitable for any model sequence launched. The objective function can be weighted according to their importance. The cycle time of each line may be different, in which case LCM is used.

Table 5. Classification of parallel Two-sided lines – mixed model

Author	Type Problem	Problem attributes					Problem features					Objective								Solution approach	Observations			
		Line	K	C	O	LL	Task	C	K	Res	O	Line	K	C	E	CO	S	LL	T			SV	W	
Zhang and Kucukkoc (2013)	Ba	-	-	-	-	-																	-	<i>Introduction of the problem</i>
Kucukkoc and Zhang (2014c)	Ba-Se	F	TBD	F	TBD	TBD	D, T3, T6	2					•				•	•					ACO	
Kucukkoc and Zhang (2014a)	Ba	F	TBD	F	TBD	TBD	D, T3, T6	2					•					•					ACO	
Kucukkoc and Zhang (2014b)	Ba-Se	F	TBD	F	TBD	TBD	D, T3, T4, T6	2					•				•	•					ACO	MILP to model the problem
Kucukkoc and Zhang (2016a)	Ba-Se	F	TBD	F	TBD	TBD	D, T3, T6	2					•					•					ACO and GA	
Kucukkoc and Zhang (2016b)	Ba	F	TBD	F	TBD	TBD	D, T3, T6	2					•					•					ACO	

4.3 Parallel U-shaped lines (PU)

Parallel U-shaped lines (PU), are two or more U-shaped lines arranged parallel to each other and balancing together (with multi-line workstations). PU was introduced by Kucukkoc and Zhang (2015b). It differs from other studies of multiple U-shaped assembly lines such as Miltenburg (1998), where only one multi-line workstation between two adjacent lines is available, and Sparling (1998) where multi-line workstations can include tasks of two or more U-lines and each U-line cannot exceed two multi-line workstation. In PU the number of multi-line workstations is not limited between two adjacent lines. In addition, PU provided several advantages over multiple U-shaped lines; according to Kucukkoc and Zhang (2015b) the most important advantage is the flexibility in producing parts at different through put rates and can include tasks from independent lines in multi-line workstations.

Figure 9 shows a schematic representation of PU, with PU having three types of workstations. At *multi-line workstations* located between two adjacent lines, the operators can perform their jobs on both lines. With *crossover workstations*, the operators located between both legs (front and back) of the inner line can perform their jobs on either of the legs. At *regular workstations* the operators perform their jobs just for only one specific line and leg.

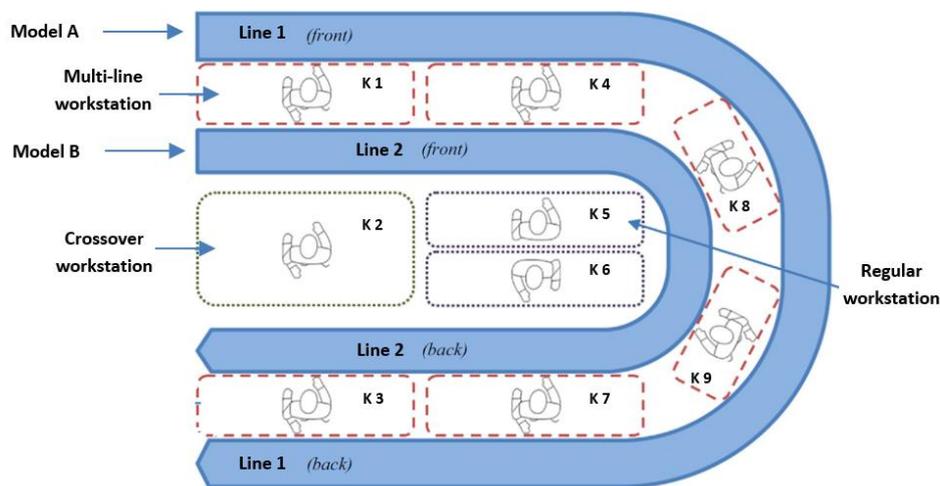


Figure 9. Schematic representation of parallel U-shaped assembly line system. Adapted from Kucukkoc and Zhang (2015b) with permission.

Additionally, as happens with two-sided lines in PU, it is possible to perform tasks on both sides of the line, for example in Figure 9, workstation 1 and 2 perform tasks on the same piece on line 2 in the same cycle time.

Table 6 and Table 7 (shown in Section 4.3.1 and 4.3.2, respectively) list the studies referring to PT chronologically.

4.3.1 Parallel U-shaped lines – Single-model (PU-SM)

A new line configuration called *Parallel U-shaped Line* (PU) was presented by Kucukkoc and Zhang (2015b). The authors developed an algorithm called *Parallel U-line Heuristic* (PUH) to deal with the problem [PU-SM, Ba|D, 2|K, LL]. PUH is based on two well-known heuristics, ranked positional weight method (RPWM) and maximum number of the immediate successors (MNIS). Each assembly line can have a different cycle time, in which case LCM is used.

Table 6. Classification of the parallel U-shaped lines – single model

Author	Type Problem	Problem attributes					Problem features					Objective								Solution approach	Observations		
		Line	K	C	O	LL	Task	C	K	Res	O	Line	<i>K</i>	<i>C</i>	<i>E</i>	<i>CO</i>	<i>S</i>	<i>LL</i>	<i>T</i>			<i>SV</i>	<i>W</i>
Kucukkoc and Zhang (2015b)	Ba	F	TBD	F	TBD	TBD	D	2					•					•				HEUR	

4.3.2 *Parallel U-shaped lines – Mixed-model (PU-MM)*

Kucukkoc and Zhang (2015c) first introduced the mixed-model PU problem to the literature. The proposal of this study is only to describe the problem [PU-MM,Ba||] and give an example of its structure.

Kucukkoc and Zhang (2017) presented the continuation of the work introduced by Kucukkoc and Zhang (2015c). This study presents the results of the research based on a new method developed for PU-MM. The PUH heuristic procedure proposed by Kucukkoc and Zhang (2015b) has been improved and adapted for the problem [PU-MM,Ba-Se|D,2|K,LL], the algorithm proposed in this article is called *mixed-model PUH* (MPUH). Model sequences of the lines have been considered to avoid non-feasible solutions and the violation of capacity limits. The MPUH algorithm generates all possible model sequence combinations and the MPS principle is used to determine the production mix on the lines. Each assembly line may have a different cycle time, in which case LCM is used.

Table 7. Classification of the parallel U-shaped lines – mixed model

Author	Type Problem	Problem attributes					Problem features					Objective								Solution approach	Observations			
		Line	K	C	O	LL	Task	C	K	Res	O	Line	K	C	E	CO	S	LL	T			SV	W	
Kucukkoc and Zhang (2015c)	Ba	-	-	-	-	-																	-	<i>Introduction of the problem</i>
Kucukkoc and Zhang (2017)	Ba-Se	F	TBD	F	TBD	TBD	D	2					•					•					HEUR	

Table 8. Classification of literature of the PALBP

Authors/year	Notation	Approach
Ağpak and Zolfaghari (2015)	[PT-SM,Ba D,T1,T2,T3,T4,T5,T6,Ws,2 K C CO LL]	MILP
Araújo et al. (2015)	[PS-SM,Ba D,T3,2,O1 C]	MILP, TS and GA
Baykasoğlu et al. (2009)	[PS-SM,Ba D,1 K,S]	ACO
Baykasoğlu et al. (2012)	[PS-SM,Ba St,1 K]	ACO
Benzer et al. (2007)	[PS-SM,Ba D,1 K]	NM
Çerçioğlu et al. (2009)	[PS-SM,Ba D,2 K]	SA
Chutima and Yothaboriban (2017)	[PS-MM,Ba-Se D,2,O1 K,S,LL,SV]	BBO
Çil et al. (2017)	[PS-SM,Ba D,Tr,1,O1 C]	MILP and BS
Esmailian et al. (2009)	[PS-MM,Ba D,2 C]	HEUR
Esmailian et al. (2011)	[PS-MM,Ba D,2 C]	TS
Esmailian et al. (2015)	[PS-MM,Ba D,2,O1 K,CO]	BLP
Gökçen et al. (2006)	[PS-SM,Ag-Ba D,2 K]	BLP and HEUR
Grangeon and Norre (2012)	[PS-SM,Ba D,1 K]	SA and HEUR
Guo and Tang (2009)	[PS-SM,Ba D,1 K]	SS
Hezer and Kara (2015)	[PS-DL-SM,Ba D,1 K]	NM
Kara and Atasagun (2013)	[PS-SM,Ba D,2,R1,R2,R3,We,Wo CO]	BLP
Kara et al. (2010)	[PS-SM,Ba D,2 K,C,T]	GP and Binary fuzzy GP
Kucukkoc and Zhang (2013)	[PT-SM,Ba D,T6,2 K]	GA
Kucukkoc and Zhang (2014a)	[PT-MM,Ba D,T3,T6,2 K,LL]	ACO
Kucukkoc and Zhang (2014b)	[PT-MM,Ba-Se D,T3,T4,T6,2 K,S,LL]	ACO
Kucukkoc and Zhang (2014c)	[PT-MM,Ba-Se D,T3,T6,2 K,S,LL]	ACO
Kucukkoc and Zhang (2015a)	[PT-SM,Ba D,T3,T4,T6,2 K]	GA
Kucukkoc and Zhang (2015b)	[PU-SM,Ba D,2 K,LL]	HEUR
Kucukkoc and Zhang (2015c)	[PU-MM,Ba]	-
Kucukkoc and Zhang (2015d)	[PT-SM,Ba D,T6,2 E]	ACO
Kucukkoc and Zhang (2016a)	[PT-MM,Ba-Se D,T3,T6,2 K,LL]	ACO and GA
Kucukkoc and Zhang (2016b)	[PT-MM,Ba D,T3,T6,2 K,LL]	ACO
Kucukkoc and Zhang (2017)	[PU-MM,Ba-Se D,2 K,LL]	HEUR
Kucukkoc et al. (2013)	[PT-SM,Ba D,T6,2 K,LL]	ACO
Mete et al. (2017)	[PS-ADL-SM,Ba D,1,L K]	ACO
Özbakir et al. (2011)	[PS-SM,Ba D,1 K,S]	ACO
Özcan (2018)	[PS-SM,Ba St,2 K]	TS
Özcan et al. (2009)	[PS-SM,Ba D,2 K,S]	TS
Özcan et al. (2010a)	[PS-MM,Ba-Se D,2 K,S]	SA
Özcan et al. (2010b)	[PT-SM,Ba D,T6,2 K]	TS
Scholl and Boysen (2009)	[PS-SM,Ag-Ba D,1 K]	BLP and B&B
Tapkan et al. (2016)	[PT-SM,Ba D,T6,Tw,2 K,Tw]	BA and ABC
Zhang and Kucukkoc (2013)	[PT-MM,Ba]	-

5. Main advantages and disadvantages

The use of parallel lines with multi-line workstations provides numerous advantages regarding the independent lines balance. In PALBP resources can be shared between two adjacent lines, in this way the number of workstations (and, thus, operators) required can be reduced. As mentioned previously, PALB is a type of multiple line, therefore it inherits all the advantages and disadvantage from multiple lines.

Advantages of adopting multiple lines or PALBs over single lines:

- Can reduce the number of operators and workstations required by the use of multi-line workstations, the operators at these workstations are able to perform their jobs on two adjacent lines. Consequently, the idle times of workstations can be reduced, thereby improving the efficiency of the whole line system. Better balances may be obtained, because more combinations of task assignments exist (Scholl, 1999).
- Increase the cycle time; single lines with short cycle times tend to produce worse line balance, but parallel lines may remove this drawback, because they can reach the same output rate as a single line, but operating with a larger cycle time and fewer workstations per line (Scholl, 1999).
- Reduce the failure sensitivity, the use of more than one assembly line reduce the risk of stopping production due to line breakdown (Lusa, 2008).
- Increase the flexibility; each line can have its own cycle time, the flexibility in the throughput levels of the lines facilitated adapting to changes in demands (Kucukkoc and Zhang, 2015b).
- Visibility and communication between operators can be improved because an operator may work on both neighbouring lines. If a problem, such as a quality problem, occurs on one of two neighbouring lines, then the operators can find and solve it quickly (Özcan et al., 2010a).
- In heterogeneous lines (lines with different models, cycle times, operators, etc), the use of parallel lines is preferable to single lines (Hemig et al., 2014).

Disadvantages of adopting multiple lines or PALBs:

- Increase in the cost of space and equipment: the increase in the number of lines causes a rise in the cost related to additional space and requirements (e.g. tools, machinery, etc.) (Lusa, 2008). The use of PAL should be considered in cases where the cost of the workforce employed is considerably higher than the cost due to additional space requirements (Scholl and Boysen, 2009).
- The possibility of producing at different output rates leads to the need to work with batches in some cases. Batches may incur extra cost and space (buffers), additionally they may increase the setup time required to allocate the workpieces in the buffer.
- Multi-line workstations may help to reduce the total number of required workstations. However, this type of workstation requires the connected lines to be synchronized somehow and a failure in a multi-line workstation may affect the performance of more than one line (Lusa, 2008).
- Each line must contain a minimum number of workstations to avoid material supply problems (due to physical distribution) (Lusa, 2008).
- The increase of the cycle time can decrease the learning effect, due to the reduction in the number of repetitions per period. In some cases this could even cause a decrease in productivity (Chakravarty and Shtub, 1988; Lusa, 2008).
- If the number of tasks that must be performed by an operator increases, the time needed to change from one task to another may no longer be considered negligible (Lusa, 2008).

6. Research proposal and conclusions

In this section we address the main research fields which require discussion, due to the lack of, or limited, attention received in the literature. The classification of the PALBP literature reveals the main important

open fields, which will be shown below. These deficiencies will be divided into aspects rarely contemplated in the PALBP literature and aspects that are not-contemplated at all.

6.1 Aspects rarely contemplated

6.1.1 Walking time

The operators that perform tasks at multi-line workstations have to move from one line to another, this movement constitutes time which is usually ignored. An impracticable balance can be generated if walking times are not considered, and an even more so in large sized assembly lines, due to the longer distance between the lines (Tapkan et al., 2016). Only a few authors considered walking time in their studies (Tapkan et al., 2016; Özcan, 2017); although walking time is considered in the procedures proposed by Gökçen et al. (2006) and Scholl and Boysen (2009), it is not considered in the computational experiment that was carried out. In addition, walking time may also arise within workstations, the movement between tasks or when the operators return to the beginning of a workstation at the end of the cycle. Walking time within a workstation is a relevant factor in large workstations, where the movement can constitute a significant amount of unproductive time.

6.1.2 Stochastic data

Stochastic data is only contemplated by Baykasoğlu et al. (2012) and Özcan (2018) in the PALBP literature. Stochastic values are present mainly in manual tasks, when a worker performs a task and this task time could vary from cycle to cycle. Normally the variation of a task's time increases with its complexity. In this sense, factors such as fatigue, learning or operator skills play an important role.

6.1.3 Automated assembly lines

Regarding the degree of automatization, workstations can be divided into manual, semi-automated, and automated workstations (Scholl, 1999). Most of the PALBP studies focus on manual lines, only Çil et al. (2017) address their study to PS-SM robotic lines. Automated workstations have become a vital industrial component, especially in the automotive sector. The use of robotic assembly lines provides several advantages over manual assembly lines, such as: improvement in productivity, product quality, manufacturing flexibility, safety, and less demand for skilled labour (Çil et al., 2017). Nevertheless, in this type of line a machinery breakdown may be more difficult to solve than in manual lines.

6.1.4 Assignment and sequencing problem

Lusa (2008) emphasised that very few studies deal with the complete, or almost complete, multiple or parallel lines balancing problem, i.e. determining the number of lines to be installed, assigning models to lines, determining the number of workstations for each line and assigning tasks to workstations. Moreover, in multi-model or mixed-model cases it is also necessary to provide a model sequencing. In PALBP literature only a few authors deal with other problems such as assignment models to lines and model sequencing (mixed/multi model). The combination of the sequencing and balancing problem may help to achieve better results. For example, in PT-MM, Kucukkoc and Zhang (2014b) compared an algorithm which includes sequencing to another algorithm with a pre-determined sequencing; the results obtained showed that the sequencing models help to achieve better results. Additionally, the assignment problem has been dealt with by Scholl and Boysen (2009), among others. However, no author considers the design of PALBP. The combined use of these problems may achieve better solutions. In accordance with the previously stated, it seems essential to consider both problems with balancing, when the nature of the problem requires it.

6.1.5 Disassembly line

Disassembly lines were introduced to the parallel lines by Hezer and Kara (2015) in the PS-SM problem. New trends, such as the circular economy, encourage the reuse of products, giving a new life to the product or its components. In this process, disassembly lines have an important role in recovering products' components. In the PALBP literature only one study focuses on this type of line, and it would seem necessary to pay more attention to this field.

6.1.6 Mixed production system (Assembly and Disassembly lines)

Mixed production systems composed for assembly and disassembly lines was introduced by Mete et al. (2017) for PS-SM. The authors stated that this design is essential for industrial practices especially on a specific operational problems and manufacturing firms. Only Mete et al. (2017) have focused on this problem.

6.1.7 Flow-line production

A key factor of PALBP is the use of multi-line workstations because they allow more possible task assignments, so it is possible to obtain better solutions. In PALBP studies all the assembly lines follow the same production flow, except Mete et al. (2017) who use two lines which products and parts move reversely. Locating the parallel assembly lines in an opposite production flow among them, may provide more task assignment possibilities, e.g. we have two assembly lines, line 1 and line 2, the production flow of line 1 going from left to right and the production flow of line 2 from right to left. Alternating the flow production of some lines, when the nature of the problem allows it, may help to achieve better results for PALBP.

6.1.8 Task restrictions

Task restrictions condition the assignment of tasks to workstations and are used to tackle more realistic problems. There are a wide range of task restrictions, such as positive and negative zoning, distance, side, etc. The use of task restrictions in the PALBP studies is not lacking, but it is necessary to consider them in the problems because the restrictions help to apply the problem to more realistic situations; moreover new restrictions, such as the task deterioration effect, should be added in order to cover more important aspects.

6.1.9 Resources restrictions

The use of additional equipment (tools or machines) or operators (or assistants) is common in the manufacturing industry. These additional resources may be needed to perform a task or can be optional; in the last case additional resources can reduce the processing time of a task. In the PALBP literature, Kara and Atasagun (2013) deals with the problem of optimally allocating the resources, but no other studies deal with this problem. Additional equipment or operators may be limited in a company and an optimal use of these resources may incur savings and improve the system efficiency.

6.1.10 Workstations restrictions

Workstations sometimes can be delimited by a specific space, where the operator has to perform a certain number of tasks. The workstation may be delimited to avoid large lines, this limitation affecting the space needed for work and therefore to space for tools or materials. Physical, technological or other limitations might affect the number of tasks that can be assigned to a workstation. Limited space in workstations has only been considered by Ağpak and Zolfaghari (2015). It is known that keeping a short assembly line is preferred for compactness thus saving space in the line layout. On the other hand, Kara and Atasagun (2013) consider workstations with different levels of equipment.

6.1.11 Workstations with more than one operator

Sometimes, some tasks must be performed by more than one operator. Usually PALBP assumes that only one operator is allowed to work on a workstation, but Kara and Atasagun (2013) deals with the possibility of having more than one operator working on the same workstation at the same time on the same workpiece. As happens with resources restrictions, the possibility in some cases of having more than one operator, due to the task requirements, should be considered and analysed. In addition, the Rabbani et al. (2012) study contemplated the possibility that an operator, in his/her idle time, can assist another operator (opposite workstation) for the time interval during which his/her primary workstation is idle. This idea might be considered in future researches, to evaluate its performance with multi-line workstations.

6.1.12 Operators with different skill levels

It is known that some operators can have a special ability to perform a task or prefer to perform one task as opposed to others. In manual assembly lines it is common to have operators with different skills levels performing a task, which means that the line efficiency may vary according to worker assignment. Authors such as Araújo et al. (2015), Esmailian et al. (2015), Chutima and Yothaboriban (2017) and Çil et al. (2017), considered this factor in their studies dealing with the PS. In contrast, in PT and PU, no study considering the operators' skill levels has been proposed.

6.1.13 Objective function

The most applied objective functions are minimising the number of workstations (K), minimising the line length (LL) and minimising the cycle time (C). Other objectives such as minimising the variation workload between workstations (S) and minimising the cost (CO) are less used. CO involves different parameters related with production, such as labour, tools, workstation, etc; optimising CO can be translated into reducing the cost per unit, which may positively affect the overall profit of a company. Few studies address objectives such as minimising line efficiency (E) (Kucukkoc and Zhang, 2015d), minimising the number of tasks that are above a predetermined value assigned to each workstation (T) (Kara et al., 2010), minimising the skill variations within workstations (SV) (Chutima and Yothaboriban, 2017) and minimising the walk distance between workstations (Tapkan et al., 2016). It is evident that most of the studies are mainly focussed on K, LL and C, which makes it necessary in future research to consider other objectives in order to cover different gaps in the literature.

6.2 Other aspects non-contemplated in the PALBP literature

6.2.1 Buffers

Parallel lines can work at different production rates. When parallel lines with different cycle times have to be balanced, the LCM approach proposed by Gökçen et al. (2006) is used by many authors. LCM allows working with a common cycle time for all the assembly lines, but this means that the lines work in batches in the same cycle (e.g. if we have two lines, the first with a cycle time of 10 tu and the second with a cycle time of 5 tu, applying LCM, we obtain a joint cycle time of 10 tu with batches of 1 and 2 pieces in line 1 and 2, respectively, for each cycle of 10 tu). In the literature there is no mention of any type of storage "buffers" in the case of producing in batches; it is assumed that no workstations allow more than one workpiece at the same workplace at the same cycle time. The use of buffers may be necessary when the production is in batches, for this reason the inclusion of buffers should be taken into account in these cases. However, the use of buffers might increase the cost of investments, floor space of the line and inventory.

6.2.2 Setup time

The setup process is not a value-added factor, and hence, setup times/costs need to be explicitly considered while scheduling decisions are made in order to increase productivity, eliminate waste, improve resource utilization, and meet deadlines (Allahverdi, 2015). However, the vast majority of existing scheduling

literature, more than 90% ignores this fact (Allahverdi, 2015). Setup time encompasses all the time that an operator dedicates to several activities related to a task. These activities involve selecting tools for different tasks, repositioning the workpiece and inspection. Setup times are related with the scheduling of tasks assigned to workstations, due to the existence of sequence-dependent setup times. The sequence in which tasks are performed at the workstation matters, since sequence-dependent setup times between tasks are present (Andrés et al., 2008). In accordance with the above, it appears necessary to consider scheduling tasks, which are usually not considered, but exist in most industrial production systems (Andrés et al., 2008).

6.2.3 *Parallel workstations/tasks*

In the literature of PALBP there is no study that evaluates the use of parallel workstations or tasks. The use of parallel workstations is possible when the time of certain tasks has a task time longer than the desired cycle time or increases the output rate. Parallel workstations provide greater flexibility in designing the production line when they are allowed, but the additional cost of equipment becomes important. The use of parallel tasks is similar to the use of parallel workstations, the effect of paralleling is to allow a task to be performed at more than one station, thereby reducing the effective task time by the number of times the facility is replicated (Pinto et al., 1975). The concept of PALB and parallel workstations/tasks should be considered and the possibility of integrating both in the same problem should be studied (Scholl and Boysen, 2009).

6.2.4 *Parallel U-shaped two-sided assembly lines*

In the literature of multiple assembly lines, Rabbani et al. (2012) address the problem of two-sided assembly lines with a multiple U-shaped layout. But in the PALBP literature there is no studies focused on this type of line layout. According to Rabbani et al. (2012), the use of several parallel U-lines might be more suitable for two-sided lines. It might be interesting to study the benefit that multi-line workstations can bring to this type of line layout.

6.2.5 *Minimise the number of operators and minimise the number of workplaces*

The objective of minimising the number of operators is usually directly related with the objective of minimising the number of workstations, because usually one operator per workstation is considered. Some problems allow the use of more than one operator per workstation; in this case it is possible to consider minimising the number of operators due to limited space, cost, etc. A disadvantage of using PALBP systems is the increment in the cost of space and equipment needed. In this way minimising the number of workplaces may be more appropriate than minimising the number of workstations and operators. Minimising the number of workplaces can help to reduce the cost of materials and tools installed in the line.

6.2.6 *Ergonomic aspects*

Traditionally in assembly lines it is very common to only consider aspects such as cost, workstations, cycle time or efficiency to be optimised (Battini et al., 2016). In the literature few studies contemplate ergonomic aspects, but in parallel lines there is no studies that consider the ergonomic aspects. The Fourth European Survey on Working Conditions published that 35% of plant and machine operators and assemblers report having regular backaches and muscular pains (Otto and Battaia, 2017). Moreover, a link between productivity and ergonomics was demonstrated by Otto and Battaia (2017). Ergonomics can produce important benefits for companies, such as improvements in productivity, safety, and workers' health, as well as reductions in injuries and absenteeism. New problems can address ergonomic aspects such as the work environment (temperature, noise), fatigue, lack of concentration due to repetitive tasks, forced work position, etc. As an example, operators working in multi-line workstations might have their ability reduced due to fatigue from walking from one line to another, this factor only affects operators of a particular type of workstation.

6.2.7 Energy-efficient line balancing

The Department of Commerce defines sustainable manufacturing “as the creation of manufactured products that use processes that minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, and consumers and are economically sound” (Urban and Chiang, 2016). Studies addressing energy efficiency on assembly line systems are quite limited and no studies address PALBP. Nowadays, reducing the consumption of energy can keep the industries competitive and reduce pollution (Mukund Nilakantan et al., 2015). In robotic assembly lines, the consumption of energy is higher than the manual lines. Li et al. (2016) indicate that the energy cost during a car manufacturing process is about 9-12% of the total manufacturing cost.

6.2.8 Semi-automated assembly lines

Semi-automated workstations are the combination of human and automatic equipment, where the human factor can be reduced to the smallest help, such as manually loading and/or unloading material supply or controlling different tasks, while the work is performed by automatic equipment. The use of machines and humans is common in the automotive industry, and increasingly, the use of cooperative robots is more widespread. It may occur in a semi-automated assembly line that the operators have idle times, due to waiting for a machine. The use of multi-line workstations may help to reduce these idle times and thereby improve the line efficiency.

6.2.9 PALBP - Multi model

The studies presented in the PALBP literature deal with single and mixed model lines, but no studies dealing with multi-model parallel lines have been presented. In their study Hemig et al. (2014) stated that the use of parallel lines over single lines is especially preferable when the lines are different in terms of models, cycle time, operators, etc. Following-up this idea, it may be possible that the more different the lines are, the more beneficial is the use of PALB.

6.2.10 Design problem

As previously mentioned in section 6.1.4, no studies deal with the complete PALBP i.e. design, assignment, balancing and sequencing, no does any study deal with the design problem. All PALBP studies assume that the number of lines is given data, but it might be interesting to contemplate line design as did Süer and Dagli (1994) and Süer (1998) for multiple lines.

6.2.11 Dynamic task time (Learning and deterioration effect)

The time duration of the tasks can be reduced due to learning effects or successive improvement of the production process or can be increased due to task deterioration effect. Learning effect is usual when the companies recruit new operators or when new tasks or procedures are added to the assembly line system. Temporary operators are commonly used to deal with demand variability. It is common for temporary operators to have learning phases in training centres and their performance enhanced. This learning effect leads to a greater productivity level, which must be contemplated by planning managers. It might be necessary to consider the learning effect due to the temporary contracts that the companies use to match their production to the demand. In the literature, no studies contemplate the learning nor deterioration effect.

6.2.12 Production systems with mix lines

In the PALBP literature, the different studies only focus on systems where the lines are single and mixed model. In the real world it is possible for a production system to be composed of single lines, mixed model lines and multi model lines. Due to the differences between lines, the use of PALB configuration may increase the efficiency of the system.

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