Pace making and worker reassignment for assembly line rebalancing

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Received: 17 April 2020 / Accepted: 19 August 2020 / Published online: 28 August 2020
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Abstract

The objective of this article is to develop a mathematical model that helps foremen rebalance assembly lines in real time. Assembly lines with a large number of workstations go through extensive line balancing to determine production rates. Once production begins, one or more workstations may not operate at predetermined production rates due to disturbances, and the assembly line requires rebalancing. Previous research largely focused on task reassignment for rebalancing. Effective and efficient tools for real-time line rebalancing are needed. This research focuses on rebalancing of unpaced and asynchronous assembly lines through pace making and worker reassignment. A mixed integer programming model is developed and its optimal solution determines which workstations pace up (increase production rates) and the amount of increase, which workstations pace down (decrease production rates) and the amount of decrease, and whether workers from certain workstations are reassigned to work at other workstations to decrease the production rates of the former and increase the production rates of the latter. Foremen may use these recommendations to rebalance assembly lines by adjusting production rates and reassigning workers. Numerical results show that the solution time of the model is less than one second, which enables real-time line rebalancing for large assembly lines.

Keywords Assembly line rebalancing · Mixed integer programming · Pace making · Unpaced and asynchronous assembly line · Worker reassignment

1 Introduction

Assembly lines have been in use for decades and are ubiquitous in today's manufacturing and production systems. As more and more products transition from mass production (make-to-stock) to mass customization (make-to-order), balancing of assembly lines aims to meet customers' demand and reduce production cost. Assembly line balancing is one of the most important decisions for large-scale production. Becker and Scholl [6] defined line balancing as assigning tasks to workstations to balance workload. Kara et al. [15] suggested several objectives of line balancing (e.g., minimizing total cost and difference in workload for workstations and maximizing production rate). There are many variations and extensions of the classical line balancing problem [6–9]. This paper investigates a common

yet challenging problem that foremen of assembly lines face on a regular basis: whether and how workers in an assembly line pace up or pace down to adjust production rates and are reassigned to different workstations if the assembly line does not operate at the production rates determined in line balancing.

When operations of an assembly line deviate from the prescribed parameters determined in line balancing, the assembly line must be rebalanced to minimize the impact caused by worker fatigue and lack of motivation, extra machine setup time, material shortage, machine breakdowns, or other disturbances. Rebalancing of assembly lines occurs in almost every production facility that owns a flow-based production [2, 36]. Foremen of assembly lines are responsible for rebalancing [33]. The main contribution of this study is the mathematical model and its solutions

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that provide an effective and efficient tool for foremen to make real-time decisions for pace making and worker reassignment in assembly lines.

In line balancing [31], each workstation is assigned a set of tasks and a fixed amount of time to complete each task. Once production begins, however, various disturbances occur and the assembly line needs to be rebalanced in response to disturbances. Certain disturbances (e.g., workstation breakdowns and shortage of supplies) pose hard constraints on a production system; they are not resolved through rebalancing of workstations and should be taken into account in the line balancing analysis [6]. Some disturbances such as skilled workers completing tasks faster than expected would cause a queue at downstream workstations. Other disturbances such as worker slowdowns due to fatigue may cause a queue at upstream workstations. These disturbances may be addressed by pace making and reassigning workers so that the assembly line is restored to the production plan determined in line balancing.

This study investigates the short-term line rebalancing problems in which real-time decisions are made in response to disturbances such as out-of-capacity buffers, worker slowdowns, and idle workstations. These disturbances either increase the cycle time of a paced or an unpaced but synchronous assembly line, or decrease the throughput of an unpaced and asynchronous assembly line [8]. The goal of rebalancing is to minimize the impact of disturbances by adjusting production rates (pacing up or pacing down) and reassigning workers between workstations. To the best of the authors' knowledge, this paper

is the first study that focuses on pace making and worker reassignment for assembly line rebalancing.

In a paced or an unpaced but synchronous assembly line, an automated material handling system (e.g., a conveyor) is used to transfer parts and products from one workstation to the other. Workers in these assembly lines are stationed at their assigned workstations. Other limitations (e.g., limited space) also prevent the assembly line from reassigning workers to different workstations. This study aims to determine pace making and worker reassignment in unpaced and asynchronous assembly lines in which workers can be reassigned to different workstations to improve the throughput when disturbances occur. The specific goal of line rebalancing in this study is to increase or decrease production rates of workstations, and therefore improve the throughput of the entire assembly line and minimize the impact of disturbances.

While many studies (e.g., [16, 22, 38]) focused on reassigning tasks to different workstations to rebalance assembly lines, there is little research on pace making and worker reassignment. Table 1 is a comparative analysis of recent literature about line balancing and rebalancing. A most common objective of these studies is to minimize workload. Some new constraints described in the studies include idle time, task reassignment, saturation limit, and retraining cost. This paper bridges the gap between real-time line rebalancing and worker reassignment. The rest of this paper is organized as follows: Sect. 2 describes related literature, Sect. 3 illustrates in detail the mathematical model for real-time line rebalancing, Sect. 4 validates the mathematical model with numerical studies, and Sect. 5 concludes the paper with discussion and future research.

Table 1 Comparative analysis of recent literature

Literature	Objective functions	New constraints proposed
[1], "An expert system to minimize operational costs in mixed-model sequencing problems with activity factor"	Minimize total production loss due to work overload and idle time	Idle time: the difference between available processing time and applied processing time
[2], "Iterated local search for dynamic assembly line rebalancing problem"	Minimize the maximum workload among workstations	Task reassignment: a task may be reassigned from one workstation to another
[3], "Workforce minimization for a mixed-model assembly line in the automotive industry"	Minimize the number of workers	Worker task assignment: a worker can start a new task after the completion of the current task
[5], "Consideration of human resources in the Mixed-model Sequencing Problem with Work Overload Minimization: Legal provisions and productivity improvement"	Minimize total work overload	Saturation limit: relationship between time used by the operator to carry out workload and the available time to work
[18], "A comparative study of exact methods for the simple assembly line balancing problem"	Minimize the number of workstations; Minimize the cycle time; Maximize the line efficiency	Not applicable
[36], "A multi-objective genetic algorithm for mixed-model assembly line rebalancing"	Minimize the number of workstations; Minimize workload variation; Minimize retraining cost of the operators	Retraining cost: one task at one workstation

2 Background

Many studies about line balancing focus on planning for manufacturing systems. Relatively few studies were conducted to investigate line balancing for service systems [25] and reconfiguration or rebalancing of assembly lines after disturbances occur [2, 16, 22, 38]. The requirement for line rebalancing changes in response to different disturbances. Significant changes of a production line (e.g., introduction of new products) require rebalancing, which is a long-term decision and equivalent to a typical line balancing problem. Other disturbances, such as significant changes in production demands and the need to remove or add workstations [13], also require line rebalancing. These mid- to long-term decisions [8] are similar to the classical line balancing problems; these decisions are valid for at least a few months and are not made frequently.

Short-term line rebalancing decisions include reassignment of workers, tasks, or supplies to different workstations, adjustment of production rates (pacing up or down within the upper and lower limits), and modification of production parameters (e.g., speed of a conveyor or capacity of a buffer). Once disturbances are resolved, the assembly line may be rebalanced to restore its original cycle time or throughput. These short-term rebalancing decisions must be made in real time in response to frequent disturbances in assembly lines. Most studies (e.g., [16, 22, 38]) on rebalancing focus on reassigning tasks to different workstations.

For both line balancing and rebalancing problems, mathematical models may be formulated and a good or optimal solution is computed to determine task assignments for workstations and the sequence of models for mixed-model assembly lines [9, 11, 24]. In line balancing problems, long-term decisions such as the workstation layout (e.g., straight and U-shaped), number of workstations, material handling systems, and others need to be made. In line rebalancing problem, part of an assembly line may be affected by frequent disturbances and quick decisions need to be made to minimize the impact.

Line balancing focuses more on mid- and long-term decisions. Line rebalancing focuses more on short-term decisions. Line balancing problems have more decision variables than rebalancing problems. Rebalancing problems must be solved within a short amount of time, whereas line balancing problems usually allow sufficient time to find an optimal solution.

2.1 Challenges in line balancing

Numerous studies were conducted to solve line balancing problems. For example, both branch and bound (e.g.,

[17]) and dynamic programming may be used to find exact solutions for simple [18, 30, 34] and generalized assembly line balancing problems [6]. Heuristic algorithms (e.g., [19, 21, 35, 37]) were used to solve line balancing problems. The objectives of various studies include maximization of profit [29], minimization of cycle time [28], work force minimization [3], and ergonomics [4, 27].

There are two main challenges related to task times in line balancing problems. First, optimal solutions to line balancing are sensitive to changes in task times [16]. Many optimal solutions are unstable; they are not optimal when there are slight changes in actual task times. Secondly, task times are not deterministic and may change depending on worker competence [20], learning effects [8, 32], training [7], and other factors. The assumption that task times remain the same is unrealistic and does not always hold. More important, many controllable or uncontrollable factors may change in a production or service system, and line rebalancing is imperative in responding to these changes.

2.2 Scope of line rebalancing

Previous studies (e.g., [26]) show that an assembly line is more efficient with a paced configuration than an unpaced setting when the assembly line is short and a single model is produced. For a long mixed-model assembly line, an unpaced setting is more efficient than a paced setting [26]. Mixed-model assembly lines are much more prevalent than single-model or multi-model assembly lines because of mass customization [5]. Since paced assembly lines often use automated material handling (e.g., conveyor systems) and specialized workstations, it is more difficult to reassign resources (e.g., tasks and workers) in paced than in unpaced assembly lines.

Available studies (e.g., [16, 22, 38]) perform line rebalancing through task reassignment or workstation reduction. These rebalancing decisions require changes in assembly line hardware and may be costly and infeasible in many situations. Although several studies (e.g., [7, 8, 20]) investigated how line rebalancing may be affected by workers' performance, there is a gap between worker reassignment and line rebalancing, which is the focus of this paper. Many unpaced production (e.g., assembly of appliances; [22]) and service lines (e.g., fast-food restaurants) require frequent rebalancing, and reassignment of workers is often the only feasible solution.

This study investigates the short-time line rebalancing problems in which real-time decisions are made in response to disturbances such as out-of-capacity buffers, worker slowdowns, and idle workstations. These disturbances decrease the throughput of an unpaced and asynchronous assembly line. The goal of rebalancing

is to minimize the impact of disturbances by adjusting production rates (pacing up or pacing down) and reassigning workers between workstations. To the best of the authors' knowledge, this is the first study that focuses on pace making and worker reassignment for assembly line rebalancing.

3 Mathematical modeling

Line rebalancing is a complex problem for an assembly line with multiple workstations and workers. Foremen of an assembly line need to adjust production rates and assign workers for a large number of workstations in real time. One of the main objectives of this research is to develop a mathematical model that provides the optimal solution to minimize the impact of disturbances on the throughput of unpaced and asynchronous assembly lines.

3.1 Assumptions

This study investigates the short-time line rebalancing problems for unpaced and asynchronous assembly lines.

In line balancing, many decisions such as the number of workstations for a set of tasks, number of workers for each workstation, asynchronous flow of jobs, precedence between tasks, buffer space, and material handling equipment are made so that workload are balanced among workstations. Line rebalancing takes these decisions made in line balancing as input and aims to adjust production rates of workstations to keep the throughput of the assembly line at the target level when disturbances occur. Short-term line rebalancing does not add or eliminate workstations, adjust the flow of jobs, or change the precedence between tasks.

3.2 Mathematical model

Table 2 summarizes parameters and variables in the mathematical model. The values of parameters are obtained from line balancing or during production. Foremen do not determine the values of parameters, which are input to the mathematical model. S_i and R_i in Table 2 represent predetermined (line balancing) and actual production rates of the i^{th} workstation, respectively. n_i is the slack in production rate when R_i is less than S_i , $n_i = S_i - R_i$; $n_i = 0$

Table 2 Parameters and variables of the mathematical model

Parameters and definition	
I	A set of workstations in an assembly line; $i, j \in I, i = 1, 2, \dots, I , j = 1, 2, \dots, I $
S_i	Production rate of the i th workstation determined in line balancing
R_i	Production rate of the i th workstation obtained from the assembly line operations
n_i	Slack in production rate of the i th workstation; $n_i = \min(R_i - S_i, 0)$
p_i	Excess in production rate of the i th workstation; $p_i = \max(R_i - S_i, 0)$
T_i	Maximum acceptable slack in production rate of the i th workstation
T_i^*	Maximum acceptable excess in production rate of the i th workstation
H_i	Threshold slack in production rate of the i th workstation at or above which the production rate of the assembly line is affected; $H_i > T_i$
H_i^*	Threshold excess in production rate of the i th workstation at or above which the worker at the workstation become idle; $H_i^* > T_i^*$
D_{ij}	The worker who works at the i th workstation may be assigned to work at the j th workstation if $D_{ij} = 1$; otherwise $D_{ij} = 0$
C_i	Maximum number of workers who may be reassigned to work at the i th workstation
M	A large integer number; $M \geq \max_i (S_i + p_i)$
g	The maximum percentage of increase in production rate; $0 \leq g \leq 1$
Variables and definition	
n_i^*	Slack in production rate of the i th workstation after the worker at the workstation paces up and/or workers from other workstations are reassigned to work at the workstation
p_i^*	Excess in production rate of the i th workstation after the worker at the workstation paces down or is reassigned to work at another workstation
x_{ij}	The worker at the i th workstation is reassigned to work at the j th workstation if $x_{ij} = 1$; otherwise $x_{ij} = 0$; $i, j \in I, i = 1, 2, \dots, I , j = 1, 2, \dots, I $
$y_{i,k}$	Level of slack; $k = 1, 2, 3$; $y_{i,1} = 1$ if $n_i \leq T_i$, otherwise $y_{i,1} = 0$; $y_{i,2} = 1$ if $T_i \leq n_i \leq H_i$, otherwise $y_{i,2} = 0$; $y_{i,3} = 1$ if $n_i \geq H_i$, otherwise $y_{i,3} = 0$
$z_{i,k}$	Level of excess; $z_{i,1} = 1$ if $p_i \leq T_i^*$, otherwise $z_{i,1} = 0$; $z_{i,2} = 1$ if $T_i^* \leq p_i \leq H_i^*$, otherwise $z_{i,2} = 0$; $z_{i,3} = 1$ if $p_i \geq H_i^*$, otherwise $z_{i,3} = 0$

otherwise. p_i is the excess in production rate when R_i is greater than S_i , $p_i = R_i - S_i$; $p_i = 0$ otherwise.

T_i and T_i^* in Table 2 are the maximum acceptable slack and excess, respectively, in the production rate of the i th workstation. H_i and H_i^* are the threshold slack and excess, respectively, in the production rate of the i th workstation. No actions are required if $n_i \leq T_i$ and $p_i \leq T_i^*$. If $T_i \leq n_i \leq H_i$ or $T_i^* \leq p_i \leq H_i^*$, foremen will be provided with an alert and may request the worker at the i th workstation to pace up if $T_i \leq n_i \leq H_i$ or pace down if $T_i^* \leq p_i \leq H_i^*$. If $n_i \geq H_i$ or $p_i \geq H_i^*$, the production rate of the i th workstation is out of control; foremen may request the worker at the i th workstation to pace up and reassign workers from other workstations to work at the i th workstation if $n_i \geq H_i$, or request the worker at the i th workstation to pace down or reassign the worker to other workstations if $p_i \geq H_i^*$. D_{ij} in Table 2 is a binary parameter. $D_{ij} = 1$ indicates the worker from the i th workstation may be reassigned to work at the j th workstation. $D_{ij} = 0$ indicates the worker from the i th workstation may not be reassigned to work at the j th workstation. The feasibility of reassigning workers from one workstation to the other is subject to the specific tasks performed at workstations, required training for workers, and other policies and rules. It is assumed that one worker is assigned to and works at each workstation in line balancing. In reality, multiple workers may be assigned to a workstation and work as a team. The team may be considered as “one” worker who works at the workstation. C_i is the maximum number of workers allowed to be reassigned to work at the i th workstation in addition to the worker who already works at the i th workstation. The worker capacity at a workstation is determined by several factors (e.g., space at a workstation). n_i^* and p_i^* in Table 2 are continuous variables representing slack and excess, respectively, in production rate of the i th workstation after line rebalancing. x_{ij} is a binary variable indicating whether the worker at the i th workstation is reassigned to work at the j th workstation. $y_{i,k}$ is a set of three binary variables ($y_{i,1}$, $y_{i,2}$, and $y_{i,3}$) that represent the level of slack in production rate of the i th workstation before line rebalancing. Similarly, $z_{i,k}$ is a set of three binary variables ($z_{i,1}$, $z_{i,2}$, and $z_{i,3}$) that represent the level of excess in production rate of the i th workstation before line rebalancing.

The mathematical model for pace making and worker reassignment is described in (1)–(18). Objective function (1) minimizes the sum of slack and excess in production rates of all workstations after line rebalancing. Constraints (2)–(4) determine whether and how workers may be reassigned from one workstation to another. Constraints (5)–(9) determine the values for three binary variables ($y_{i,1}$, $y_{i,2}$, and $y_{i,3}$) for each workstation before line rebalancing. These three binary values are determined by the amount of slack in the production rate of each workstation.

Constraint (9) ensures that one and only one of the three binary variables, $y_{i,1}$, $y_{i,2}$, and $y_{i,3}$, is 1 and the other two are 0 for the i th workstation.

If $y_{i,1} = 1$, the worker at the i th workstation does not pace up nor do workers from other workstations are reassigned to work at the i th workstation. If $y_{i,2} = 1$, constraint (10) determines the slack in production rate of the i th workstation after the worker at the workstation paces up. The maximum percentage of increase in production rate, g , varies and depends on assembly lines. Groover [14] suggested that $g = 40\%$. Devotta [12] stated that 100% pace was the normal pace and the production rate could decrease to 60% or increase to 140% of the normal pace. In automotive assembly lines [1], workers may increase the production rate by 20% of the actual production rate. Foremen may adjust the maximum increase in production rate for line rebalancing. If $y_{i,3} = 1$, constraint (11) determines the slack in production rate of the i th workstation after the worker at the workstation paces up and workers from other workstations are reassigned to work at the workstation. The maximum increase in production rate ($gR_i + \sum_{j \neq i, j \in I} p_j x_{j,i}$) is the outcome of both worker paces up at the workstation and help from workers reassigned to work at the workstation. Constraints (12)–(18) mirror constraints (5)–(11) and manage excess in production rates. The mathematical model is a mixed integer programming model.

$$\min \sum_{i=1}^{|I|} (n_i^* + p_i^*) \quad (1)$$

Subject to

$$\sum_{j \neq i, j \in I} x_{ij} \leq 1, \forall i \in I \quad (2)$$

$$\sum_{j \neq i, j \in I} x_{ji} \leq C_i, \forall i \in I \quad (3)$$

$$x_{ij} \leq D_{ij}, \forall i, j \in I \quad (4)$$

$$n_i y_{i,1} \leq T_i, \forall i \in I, \quad (5)$$

$$T_i (1 - y_{i,1}) \leq n_i, \forall i \in I \quad (6)$$

$$n_i (1 - y_{i,3}) \leq H_i, \forall i \in I \quad (7)$$

$$H_i y_{i,3} \leq n_i, \forall i \in I \quad (8)$$

$$\sum_{k=1}^3 y_{i,k} = 1, \forall i \in I \quad (9)$$

$$n_i^* + gR_i y_{i,2} + M y_{i,3} \geq n_i, \forall i \in I \quad (10)$$

$$n_i^* + gR_i + \sum_{j \neq i, j \in I} p_j x_{j,i} + M(1 - y_{i,3}) \geq n_i, \forall i \in I \quad (11)$$

$$p_i z_{i,1} \leq T_i^*, \forall i \in I \quad (12)$$

$$T_i^* (1 - z_{i,1}) \leq p_i, \forall i \in I \quad (13)$$

$$p_i (1 - z_{i,3}) \leq H_i^*, \forall i \in I \quad (14)$$

$$H_i^* z_{i,3} \leq p_i, \forall i \in I \quad (15)$$

$$\sum_{k=1}^3 z_{i,k} = 1, \forall i \in I \quad (16)$$

$$p_i^* + 0.4R_i z_{i,2} + M z_{i,3} \geq p_i, \forall i \in I \quad (17)$$

$$p_i^* + 0.4R_i + \sum_{j \neq i, j \in I} n_j x_{j,i} + M(1 - z_{i,3}) \geq p_i, \forall i \in I \quad (18)$$

$$n_i^*, p_i^* \geq 0, x_{i,j}, y_{i,k}, z_{i,k} = 0 \text{ or } 1, i = 1, 2, \dots, |I|, \\ j = 1, 2, \dots, |I|, k = 1, 2, 3$$

A mathematical model's complexity depends on the model detail, which includes the number of feasible solutions, decision variables, and constraints [10]. The complexity of the mathematical model described in (1)–(18) depends on the total number of workstations ($|I|$) in an assembly line, which determines the numbers of constraints and decision variables in the model. There are $|I|^2 + 16|I|$ constraints and $|I|^2 + 8|I|$ decision variables in this mixed integer linear programming model. The order of the complexity of this mathematical model is $O(|I|^2)$.

4 Numerical studies and validation

Production of an unpaced and asynchronous assembly line with multiple workstations may encounter various situations depending on whether and how many workstations have slack or excess in their production rates. To validate the mathematical model described in Sect. 3, seven different scenarios (I–VII) are defined and corresponding case studies are developed and solved. These seven scenarios

represent all possible variations in production rates for unpaced and asynchronous assembly lines. Data used in case studies are abstracted from several assembly lines.

Scenario I No slack or excess in production rate of any workstation ($n_i = p_i = 0$). The assembly line operates at production rates recommended by line balancing.

Scenario II All workstations have slack in production rates ($n_i > 0$ and $p_i = 0$); they assemble fewer products than what is required by line balancing. This may happen at the beginning of production or right after the assembly line resumes operations after incidents. The assembly line may be operating in an extended warm-up period. Rebalancing of the assembly line may be necessary depending on the level of slack.

Scenario III All workstations have excess in production rates ($n_i = 0$ and $p_i > 0$); they assemble more products than what is required by line balancing. This may happen due to overreaction in response to slack in production rates or pressure from upstream workstations with excess in production rates. For example, an upstream workstation assembles more products than what is required and pushes products to downstream workstations, which may intentionally or sometimes unintentionally expedite production to absorb the additional products. Rebalancing of the assembly line may be necessary depending on the level of excess.

Scenario IV Some but not all workstations have slack in production rates ($n_i > 0$ and $p_i = 0$ for some workstations, and $n_i = p_i = 0$ for others). This scenario is similar to Scenario II, but has fewer workstations that have slack in production rates. Rebalancing of the assembly line may be necessary depending on the level of slack.

Scenario V Some but not all workstations have excess in production rates ($n_i = 0$ and $p_i > 0$ for some workstations, and $n_i = p_i = 0$ for others). This scenario is similar to Scenario III, but has fewer workstations that have excess in production rates. Rebalancing of the assembly line may be necessary depending on the level of excess.

Scenario VI Some workstations have slack in production rates ($n_i > 0$ and $p_i = 0$), some have excess in production rates ($n_i = 0$ and $p_i > 0$), and the others do not have slack or excess in production rates ($n_i = p_i = 0$). This scenario describes a common situation of an assembly line with multiple workstations that operate differently with respect to production rates determined by line balancing. Rebalancing of the assembly line may be necessary depending on the level of slack and excess.

Scenario VII Some workstations have slack in production rates ($n_i > 0$ and $p_i = 0$) and others have excess in production rates ($n_i = 0$ and $p_i > 0$). This scenario indicates that production rates determined by line bal-

ancing are not practical and none of the workstations in the assembly line operates at the target production rate. Rebalancing of the assembly line may be necessary depending on the level of slack and excess.

4.1 Case studies with three and five workstations

A case study for each of the seven scenarios is developed to validate the mathematical model. An assembly line with three workstations ($i = 1, 2, 3$) is used in all seven case studies. It is assumed that the production rate determined in line balancing is 100 units per unit time for all three workstations ($S_i = 100, i = 1, 2, 3$). A worker who works at a workstation may be reassigned to work at any of the two other workstations ($D_{ij} = 1, i = 1, 2, 3, j = 1, 2, 3, i \neq j$). Each workstation may get help from at most one

more worker from other workstations ($C_i = 1, i = 1, 2, 3$). Table 3 summarizes the results of the mathematical model for all seven case studies. The General Algebraic Modeling System (GAMS) 24.0.2 is used to solve the mathematical model.

Results in Table 3 show that workers are not reassigned from one workstation to another ($x_{ij} = 0$). The slacks and excesses in the seven case studies are relatively small. The maximum slack or excess is 10 (Scenarios II–VII). The case studies allow a worker to pace up or pace down as much as 40% of a workstation's actual production rate [12, 14]. The relatively small slack and excess may be corrected through pacing up or pacing down by workers; reassignment of workers is not required. The maximum solution time is 0.032 s, indicating that the mathematical model may be used to rebalance small assembly lines in real time.

Table 3 Results of seven case studies

Scenario	Workstation i	S_i	R_i	n_i	p_i	T_i	T_i^*	H_i	H_i^*	Model solution for rebalancing	Objective value	Model solution time (s)
I	1	100	100	0	0	5	5	10	10	$x_{ij} = 0$ $n_i^* = p_i^* = 0$	0	0.016
	2	100	100	0	0	5	5	10	10			
	3	100	100	0	0	5	5	10	10			
II	1	100	95	5	0	5	5	10	10	$x_{ij} = 0$ $n_1^* = n_2^* = 0$ $n_3^* = 1$ $p_i^* = 0$	1	0.032
	2	100	90	10	0	5	5	10	10			
	3	100	99	1	0	5	5	10	10			
III	1	100	110	0	10	5	5	10	10	$x_{ij} = 0$ $n_i^* = 0$ $p_1^* = p_2^* = 0$ $p_3^* = 1$	1	0.031
	2	100	105	0	5	5	5	10	10			
	3	100	101	0	1	5	5	10	10			
IV	1	100	100	0	0	5	5	10	10	$x_{ij} = 0$ $n_i^* = p_i^* = 0$	0	0.032
	2	100	95	5	0	5	5	10	10			
	3	100	90	10	0	5	5	10	10			
V	1	100	100	0	0	5	5	10	10	$x_{ij} = 0$ $n_i^* = p_i^* = 0$	0	0.031
	2	100	110	0	10	5	5	10	10			
	3	100	105	0	5	5	5	10	10			
VI	1	100	100	0	0	5	5	10	10	$x_{ij} = 0$ $n_i^* = p_i^* = 0$	0	0.031
	2	100	110	0	10	5	5	10	10			
	3	100	90	10	0	5	5	10	10			
VII	1	100	95	5	0	5	5	10	10	$x_{ij} = 0$ $n_i^* = p_i^* = 0$	0	0.031
	2	100	110	0	10	5	5	10	10			
	3	100	90	10	0	5	5	10	10			

Figure 1 shows a case study of five workstations in which worker reassignment helps rebalance an assembly line. Workstation 1 operates as expected according to line balancing. Workstations 2 and 5 have slack in production rate, whereas workstations 3 and 4 have excess in production rate. The mathematical model uses these input data and computes an optimal solution that rebalances the assembly line. The optimal solution suggests workstations 2 and 5 pace up and workstation 3 pace down. Since the slack at workstation 5 exceeds the threshold slack ($H_i = 10$ in Table 3) and the excess at workstation 4 exceeds the threshold excess ($H_i^* = 10$ in Table 3), the optimal solution to the model also suggests that the worker at workstation 4 be reassigned to workstation 5.

4.2 Line rebalancing of one-hundred workstations

Large assembly lines may include a few dozens of workstations (e.g., automotive assembly lines; [13]). To validate the mathematical model for large assembly lines, two assembly lines of 100 workstations each are rebalanced using the methodology developed in this article. In both assembly lines, a worker who works at a workstation may be reassigned to work at any other workstations ($D_{ij} = 1$, $i = 1, \dots, 100$, $j = 1, \dots, 100$, $i \neq j$). Each workstation may

get help from at most one more worker from other workstations ($C_i = 1$, $i = 1, \dots, 100$). Without losing generality, it is assumed that the production rate determined in line balancing is 100 units per unit time for all 100 workstations ($S_i = 100$, $i = 1, \dots, 100$). The data for these two assembly lines are abstracted from literature (e.g., [13] and real-world assembly lines).

The maximum acceptable slack T_i and excess T_i^* in production rates are assumed to be 5 ($T_i = T_i^* = 5$, $i = 1, \dots, 100$). The threshold slack H_i and excess H_i^* in production rate are assumed to be 15 ($H_i = H_i^* = 15$, $i = 1, \dots, 100$). The actual production rate R_i (Appendices 1 and 2) is randomly and uniformly generated between 60 (40% less than 100) and 140 (40% more than 100). The values for parameters T_i , T_i^* , H_i , H_i^* , and R_i ensure that (a) some workstations have slack in production rates ($n_i > 0$), some workstations have excess in production rates ($p_i > 0$), and others do not have slack or excess in production rate ($n_i = p_i = 0$); (b) among workstations with slack in production rates, some have slack that is acceptable ($n_i \leq T_i$), some have slack that is below the threshold ($T_i \leq n_i \leq H_i$) but require pacing up, and others have slack that is above threshold ($n_i \geq H_i$) and require both pacing up and help from workers from other workstations; and (c) among workstations with excess in production

Fig. 1 Line rebalancing of five workstations

rates, some have excess that is acceptable ($p_i \leq T_i^*$), some have excess that is below the threshold ($T_i^* \leq p_i \leq H_i^*$) but require pacing down, and others have excess that is above threshold ($p_i \geq H_i^*$) and require pacing down and/or reassigning workers to other workstations. Table 4 summarizes parameter values (Appendix 1) of the first assembly line with 100 workstations, which are divided into seven groups depending on the level of slack and excess in production rates.

Workstations in groups 1, 2, and 5 in Table 4 do not require any actions. Workstations in groups 3 and 4 need to pace up, whereas workstations in groups 6 and 7 need to pace down. In addition, workers who work at workstations in group 7 may be reassigned to workstations in group 4 to increase their production rates. The mathematical model for rebalancing this assembly line of 100 workstations is solved using GAMS 24.0.2 on a desktop computer with 8.00 GB RAM and 64-bit Windows operating system. The solution time is less than one second, indicating the mathematical model developed in Sect. 3 is computationally efficient. Table 5 summarizes worker reassignments from one workstation to the other. For example, the worker at the 18th workstation is reassigned to work at the 24th workstation. Total 10 workers are reassigned from one workstation to another. Table 6 summarizes production rate changes in percentage after pacing up or pacing down. The optimal objective function value is 17, which is the sum of deviations (slacks and excesses) in production rates of workstations in groups 1, 2, and 5. All other workstations require rebalancing and the model solution ensures that their production rates $R_i = S_i$ after rebalancing.

Table 7 summarizes parameter values (Appendix 2) of the second assembly line with 100 workstations, which are divided into the same seven groups depending on the level of slack and excess in production rates. The mathematical model for rebalancing this assembly line of 100 workstations is solved using GAMS 24.0.2 on a desktop computer with 8.00 GB RAM and 64-bit Windows operating system. The solution time is again less than one second. Table 8 summarizes worker reassignments from one workstation to the other. Total 12 workers are reassigned from one workstation to another. Table 9 summarizes production rate changes in percentage after pacing up or pacing down.

4.3 Computational complexity

The model is implemented in the GAMS 24.0.2 and solved using the CPLEX branch-and-cut algorithm and data extracted from assembly lines. The computational complexity of the branch-and-cut algorithm is difficult to analyze and tight bounds are not available [23]. Table 10 summarizes the solution times of the CPLEX branch-and-cut algorithm as the number of workstations increases. Figure 2 shows how solution times in Table 10 changes as the number of workstations increases. The curve in Fig. 2 is best described by a polynomial function with an order of four, indicating that the computational complexity of solving the mathematical model is $O(|I|^4)$.

Table 4 Slacks and excesses in production rates of one-hundred workstations (Appendix 1)

Group	Slack (n_i) and excess (p_i)	Workstations (i)	Number of workstations
1	$n_i = p_i = 0$	3, 77, 97	3
2	$n_i \leq T_i$ and $p_i = 0$	1, 44, 49, 66, 78	5
3	$T_i \leq n_i \leq H_i$ and $p_i = 0$	4, 12, 20, 25, 27, 33, 42, 43, 52, 59, 61, 64, 83, 85, 89, 93, 100	17
4	$n_i \geq H_i$ and $p_i = 0$	5, 6, 11, 21, 22, 24, 36, 37, 46, 47, 50, 55, 68, 69, 70, 71, 74, 75, 76, 86, 88, 92, 94, 95, 96, 98	26
5	$p_i \leq T_i^*$ and $n_i = 0$	34, 35	2
6	$T_i^* \leq p_i \leq H_i^*$ and $n_i = 0$	10, 16, 18, 30, 48, 51, 54, 60, 65	9
7	$p_i \geq H_i^*$ and $n_i = 0$	2, 7, 8, 9, 13, 14, 15, 17, 19, 23, 26, 28, 29, 31, 32, 38, 39, 40, 41, 45, 53, 56, 57, 58, 62, 63, 67, 72, 73, 79, 80, 81, 82, 84, 87, 90, 91, 99	38
Total			100

Table 5 Worker reassignment for the assembly line of one-hundred workstations (Appendix 1)

Worker reassignment between workstations									
18 → 24	32 → 36	41 → 95	56 → 5	57 → 6	58 → 68	62 → 94	63 → 98	67 → 88	81 → 37

Table 6 Production rate changes for the assembly line of one-hundred workstations (Appendix 1)

Action	Workstation	Production rate change (%)	Workstation	Production Rate change (%)	Workstation	Production Rate change (%)
Pace up	4	0.124	5	0.355	6	0.274
	11	0.190	12	0.111	20	0.136
	21	0.250	22	0.351	24	0.400
	25	0.111	27	0.149	33	0.087
	42	0.064	43	0.111	46	0.299
	47	0.351	50	0.389	52	0.099
	55	0.351	59	0.087	61	0.087
	64	0.087	68	0.238	69	0.205
	70	0.176	71	0.299	74	0.316
	75	0.250	76	0.250	83	0.053
	85	0.064	86	0.299	89	0.136
	92	0.333	93	0.124	94	0.049
	96	0.316	100	0.111		
Pace down	2	-0.237	7	-0.160	8	-0.237
	9	-0.145	10	-0.048	13	-0.206
	14	-0.254	15	-0.225	16	-0.099
	17	-0.265	18	-0.083	19	-0.275
	23	-0.242	26	-0.270	28	-0.275
	29	-0.194	30	-0.065	31	-0.254
	32	-0.030	38	-0.248	39	-0.180
	40	-0.265	41	-0.281	45	-0.231
	48	-0.115	51	-0.107	53	-0.160
	54	-0.057	60	-0.048	63	-0.021
	65	-0.091	67	-0.022	72	-0.237
	73	-0.286	79	-0.206	80	-0.145
	81	-0.022	82	-0.242	84	-0.265
	87	-0.248	90	-0.153	91	-0.270
	99	-0.281				

Table 7 Slacks and excesses in production rates of one-hundred workstations (Appendix 2)

Group	Slack (n_i) and excess (p_i)	Workstations (i)	Number of Workstations
1	$n_i = p_i = 0$	None	0
2	$n_i \leq T_i$ and $p_i = 0$	7, 18, 20, 32, 45, 79	6
3	$T_i \leq n_i \leq H_i$ and $p_i = 0$	1, 2, 3, 5, 8, 9, 10, 14, 25, 27, 43, 52, 56, 78, 89, 98, 100	17
4	$n_i \geq H_i$ and $p_i = 0$	11, 13, 19, 23, 29, 31, 40, 41, 47, 50, 53, 54, 66, 67, 68, 70, 73, 81, 82, 85, 86, 87, 91, 92, 94, 95, 99	27
5	$p_i \leq T_i^*$ and $n_i = 0$	48, 63, 77, 80, 96, 97	6
6	$T_i^* \leq p_i \leq H_i^*$ and $n_i = 0$	12, 15, 30, 34, 37, 44, 55, 59, 64, 69, 76, 83	12
7	$p_i \geq H_i^*$ and $n_i = 0$	4, 6, 16, 17, 21, 22, 24, 26, 28, 33, 35, 36, 38, 39, 42, 46, 49, 51, 57, 58, 60, 61, 62, 65, 71, 72, 74, 75, 84, 88, 90, 93	32
Total			100

Table 8 Worker reassignment for the assembly line of one-hundred workstations (Appendix 2)

Worker reassignment between workstations											
4→66	12→86	21→99	35→70	51→68	55→31	60→40	61→53	62→29	64→73	65→11	88→67

Table 9 Production rate changes for the assembly line of one-hundred workstations (Appendix 2)

Action	Workstation	Production rate change (%)	Workstation	Production rate change (%)	Workstation	Production rate change (%)
Pace up	1	0.176	2	0.075	3	0.111
	5	0.176	8	0.124	9	0.124
	10	0.124	11	0.056	13	0.190
	14	0.111	19	0.282	20	0.053
	23	0.333	25	0.124	27	0.075
	29	0.187	31	0.225	40	0.361
	41	0.370	43	0.163	45	0.053
	47	0.351	50	0.282	52	0.176
	53	0.167	54	0.389	56	0.099
	66	0.048	67	0.016	70	0.254
	73	0.381	78	0.087	81	0.250
	82	0.389	85	0.266	86	0.225
	87	0.266	89	0.163	91	0.282
	92	0.282	94	0.316	95	0.220
	98	0.111	99	0.029	100	0.136
Pace down	6	−0.174	12	−0.115	15	−0.091
	16	−0.153	17	−0.219	22	−0.153
	24	−0.219	26	−0.237	28	−0.145
	30	−0.115	33	−0.231	34	−0.065
	36	−0.231	37	−0.065	38	−0.138
	39	−0.187	42	−0.174	44	−0.130
	46	−0.174	48	−0.048	49	−0.200
	51	−0.022	55	−0.115	57	−0.200
	58	−0.180	59	−0.099	64	−0.115
	69	−0.091	71	−0.153	72	−0.160
	74	−0.206	75	−0.242	76	−0.130
	83	−0.115	84	−0.270	90	−0.180
	93	−0.242	97	−0.048		

Table 10 Solution times of the mathematical model

Number of Workstations	3	5	10	50	100	250	500	1000
Solution time (s)	0.016	0.032	0.064	0.350	0.950	1.500	1.900	2.520

5 Conclusions and future work

This paper develops a new methodology to rebalance unpaced and asynchronous assembly lines through pace making and reassignment of workers. A mixed integer programming model is developed to find the optimal solution for line rebalancing. Seven case studies with three and five workstations and two large assembly lines with 100 workstations each are used to validate the mathematical model and line rebalancing methodology. The solution time in all cases is less than one second. Results show that the methodology developed in this article may be used to rebalance large assembly lines and provide assembly

line foremen with real-time recommendations for line rebalancing.

Parameters of the mathematical model are obtained from line balancing and assembly line operations. When production rates of workstations deviate from predetermined values, foremen use the parameters as input and run the mathematical model to find the optimal worker reassignment and production rate adjustment in real time. Foremen use the optimal solution of the mathematical model and make informed decisions about how workers may be reassigned between workstations and how production rates should be adjusted to minimize the impact of various disturbances that are unavoidable in assembly lines.

Fig. 2 Solutions times (Table 10) of the mathematical model

Assembly line foremen may also determine the maximum allowable increase (pacing up) and decrease (pacing down) for each workstation. Larger increase and decrease help smooth workload among workstations. This may be feasible at the beginning of a shift when workers are more flexible in productivity. Smaller increase and decrease limit workstations' ability to smooth workload through pacing up or pacing down; more workers are reassigned between workstations to reduce the impact of disturbances. This becomes likely toward the end of a shift when workers experience fatigue, or for a shift in which most workers have limited experience with assembly tasks. The mathematical model enables foremen to adjust the maximum allowable increase and decrease in production rates and optimally control the assembly line with realistic solutions.

Future research may incorporate and implement the mathematical model in a decision support system with a user-friendly interface for assembly line foremen to interact with the model and make informed decisions. The model developed in this article focuses on production systems and assembly lines. In the future, the mathematical model may be revised and expanded for service

systems, which face unique challenges such as highly stochastic demand, and the need to minimize customer wait time and maximize the number of customers served. In addition, the methodology developed in this article may be generalized to solve other task assignment and real-time reassignment problems. Another promising research direction is to use the branch, bound, and remember method [17] to tackle the line rebalancing problem.

Availability of data and material Data are included in appendices

Compliance with ethical standards

Conflict of interest Not applicable

Appendix 1

Actual production rates (R'_i 's) and corresponding slacks (n'_i 's) and excesses (p'_i 's) of the first assembly line of one-hundred workstations ($i = 1, \dots, 100$)

i	R_i	n_i	p_i	i	R_i	n_i	p_i	i	R_i	n_i	p_i	i	R_i	n_i	p_i
1	97	3	0	26	137	0	37	51	112	0	12	76	80	20	0
2	131	0	31	27	87	13	0	52	91	9	0	77	100	0	0
3	100	0	0	28	138	0	38	53	119	0	19	78	99	1	0
4	89	11	0	29	124	0	24	54	106	0	6	79	126	0	26
5	62	38	0	30	107	0	7	55	74	26	0	80	117	0	17
6	62	38	0	31	134	0	34	56	116	0	16	81	134	0	34
7	119	0	19	32	134	0	34	57	121	0	21	82	132	0	32
8	131	0	31	33	92	8	0	58	122	0	22	83	95	5	0
9	117	0	17	34	103	0	3	59	92	8	0	84	136	0	36
10	105	0	5	35	101	0	1	60	105	0	5	85	94	6	0
11	84	16	0	36	70	30	0	61	92	8	0	86	77	23	0
12	90	10	0	37	69	31	0	62	136	0	36	87	133	0	33
13	126	0	26	38	133	0	33	63	140	0	40	88	69	31	0
14	134	0	34	39	122	0	22	64	92	8	0	89	88	12	0
15	129	0	29	40	136	0	36	65	110	0	10	90	118	0	18
16	111	0	11	41	139	0	39	66	97	3	0	91	137	0	37
17	136	0	36	42	94	6	0	67	134	0	34	92	75	25	0
18	109	0	9	43	90	10	0	68	63	37	0	93	89	11	0
19	138	0	38	44	98	2	0	69	83	17	0	94	61	39	0
20	88	12	0	45	130	0	30	70	85	15	0	95	64	36	0
21	80	20	0	46	77	23	0	71	77	23	0	96	76	24	0
22	74	26	0	47	74	26	0	72	131	0	31	97	100	0	0
23	132	0	32	48	113	0	13	73	140	0	40	98	63	37	0
24	65	35	0	49	96	4	0	74	76	24	0	99	139	0	39
25	90	10	0	50	72	28	0	75	80	20	0	100	90	10	0

Appendix 2

Actual production rates (R'_i 's) and corresponding slacks (n'_i 's) and excesses (p'_i 's) of the second assembly line of one-hundred workstations ($i = 1, \dots, 100$)

i	R_i	n_i	p_i	i	R_i	n_i	p_i	i	R_i	n_i	p_i	i	R_i	n_i	p_i
1	85	15	0	26	131	0	31	51	137	0	37	76	115	0	15
2	93	7	0	27	93	7	0	52	85	15	0	77	101	0	1
3	90	10	0	28	117	0	17	53	66	34	0	78	92	8	0
4	134	0	34	29	64	36	0	54	72	28	0	79	98	2	0
5	85	15	0	30	113	0	13	55	113	0	13	80	103	0	3
6	121	0	21	31	71	29	0	56	91	9	0	81	80	20	0
7	97	3	0	32	97	3	0	57	125	0	25	82	72	28	0
8	89	11	0	33	130	0	30	58	122	0	22	83	113	0	13
9	89	11	0	34	107	0	7	59	111	0	11	84	137	0	37
10	89	11	0	35	116	0	16	60	117	0	17	85	79	21	0
11	71	29	0	36	130	0	30	61	123	0	23	86	71	29	0
12	113	0	13	37	107	0	7	62	124	0	24	87	79	21	0
13	84	16	0	38	116	0	16	63	104	0	4	88	137	0	37
14	90	10	0	39	123	0	23	64	113	0	13	89	86	14	0
15	110	0	10	40	61	39	0	65	125	0	25	90	122	0	22

i	R_i	n_i	p_i	i	R_i	n_i	p_i	i	R_i	n_i	p_i	i	R_i	n_i	p_i
16	118	0	18	41	73	27	0	66	63	37	0	91	78	22	0
17	128	0	28	42	121	0	21	67	62	38	0	92	78	22	0
18	96	4	0	43	86	14	0	68	66	34	0	93	132	0	32
19	78	22	0	44	115	0	15	69	110	0	10	94	76	24	0
20	95	5	0	45	95	5	0	70	67	33	0	95	82	18	0
21	128	0	28	46	121	0	21	71	118	0	18	96	103	0	3
22	118	0	18	47	74	26	0	72	119	0	19	97	105	0	5
23	75	25	0	48	105	0	5	73	63	37	0	98	90	10	0
24	128	0	28	49	125	0	25	74	126	0	26	99	70	30	0
25	89	11	0	50	78	22	0	75	132	0	32	100	88	12	0

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