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Optimizing Dynamic Takt Time in Single Model Assembly Line Balancing Problem Considering Flexible Assignment Using Mathematical Modelling

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ABSTRACT

A decline in productivity within manufacturing processes is often attributed to inefficiencies in time management and fluctuating customer demand. To address these challenges, this study proposes a mathematical modeling approach to optimize assembly line balancing by incorporating task assignment flexibility and lean manufacturing principles. The model aims to enhance workstation efficiency by minimizing idle time and maximizing productivity through dynamic takt time adjustments. The formulation includes an objective function and constraints that reflect cycle time limitations, task precedence, and production capacity. Mathematical simulations demonstrate a significant improvement in production line performance, with line efficiency reaching 96.66%, a reduction in balance delay to 3.33%, and a smoothness index of 98.77%. The integration of process consolidation and trajectory minimization proves effective in optimizing working time while reducing the number of operators and machines required. These findings highlight the potential of lean-based mathematical modeling to substantially improve efficiency in production systems.

Keywords: *Balance delay, Cycle time, lean, Line balancing, Takt time.*

Introduction

The assembly line is a popular method used in mass-production environments. It allows workers with limited training to assemble products using fixed machines and robots. The assembly line consists of multiple workstations organized using a specific transportation system [1][2][3]. This system moves workpieces through the assembly line from one station to the next at a constant speed, determining the production speed. The cycle time limits the tasks performed on the workpiece at each workstation. Assembly trajectory balance aims to improve efficiency by maximizing the ratio between throughput and cost. To achieve balance in the trajectory, assembly trajectory planning is necessary so that the machines of each workstation can operate with a balanced load. [4] The section responsible for managing the assembly trajectory regulates the balance. Henry Ford's innovative assembly line, which used belts as factory drives, revolutionized car manufacturing. This allowed workers to build cars one piece at a time, rather than one car, through the principle of 'division of labor,' which requires workers to focus on one activity to ensure quality [5][6].

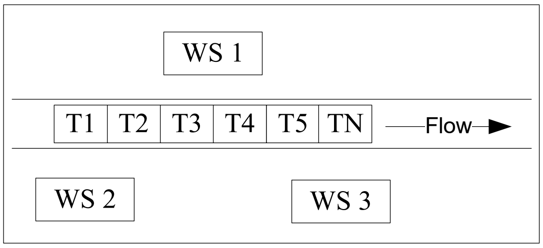

Figure 1. Line balancing concept

An assembly line is a production flow system where productive units perform operations. Workpieces successively go through stations that are moved along the trajectory and are usually carried out through a transportation system, such as a conveyor belt. Assembly lines were initially developed for the cost efficiency of mass production of standard products, designed to exploit high labor specialization. The assembly line is the most widely used method in production systems. The main objective of assembly line design is to improve efficiency and reduce costs [7][8][9].

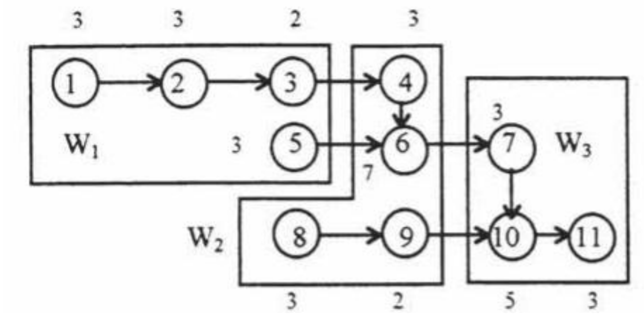

Figure.2. Task assignment

In modern production, the speed of assembly is often determined by the available time capacity. This approach is known as lean manufacturing. The essential factor determining production speed in the Lean concept is the takt time. Therefore, applying the Lean concept in the Line Balancing method is expected to use working time on each track more effectively [10][11].

If the cycle is below the takt time, overproduction will happen because line production will produce more, but if the cycle time is larger than the takt time, underproduction will happen because line production cannot produce as demand. Cycle time talks about what we can do; instead of hearing the customer's voice, Takt time talks about what we need to do [12].

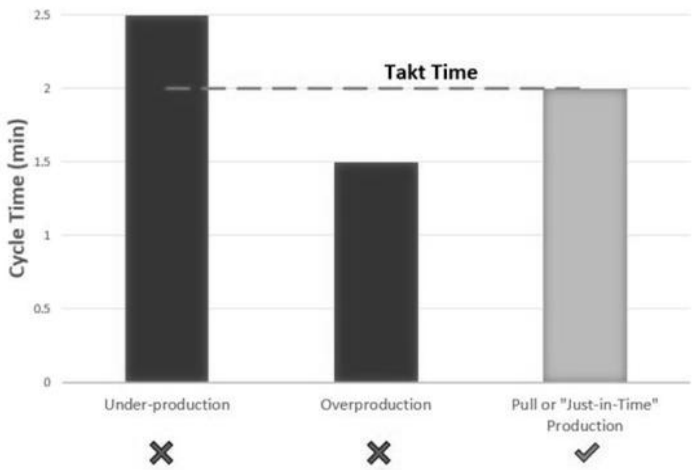

Figure 3. Cycle time and takt time comparison

A company specializing in manufacturing sometimes has observed a decline in productivity, which may be attributed to the challenges posed by fluctuating production demands and inefficient production processes. If line efficiency can be optimized, productivity will increase, too.

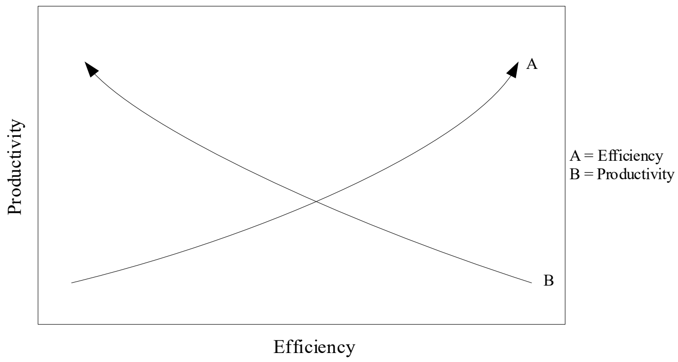

Figure. 4. Comparison of efficiency to productivity

The productivity levels might vary, causing unstable productivity due to the suboptimal use of working time at each workstation [13]. Inefficient working time may also result in low workstation utilities during production. Please refer to Figure 5 for the graph of workstation utility.

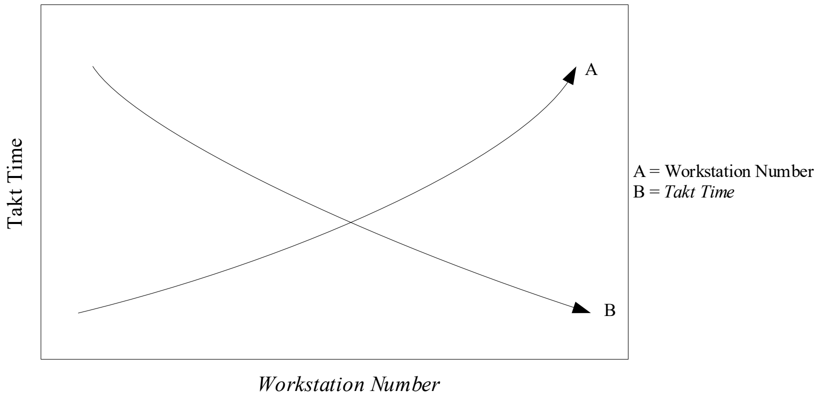

Figure 5. Comparison of workstation numbers to takt time

Figure 5 presents a comparative analysis between the number of workstations and takt time. Curve A illustrates the sequential distribution of workstations along the production line, serving as a task allocation. Curve B reflects the takt time, which denotes the pace at which products must be completed to align with customer demand. When the curves converge, it indicates a well-balanced system where the workload is evenly distributed across workstations, and the production rhythm is maintained efficiently. Conversely, significant divergence between the curves suggests potential inefficiencies, such as bottlenecks or underutilized resources, which may lead to increased idle time or overburdened stations.

The ability to respond to unforeseen disturbances during the manufacturing process by adjusting the schedule is an essential feature of assembly systems. Control flexibility allows for various task assignments for similar or different product types. However, due to the complex system configuration and the diverse states of the system, achieving an optimal scheduling solution in real-time control takes time [12][14].

Using a lean approach, the researcher should examine work trajectories to improve production efficiency. The study aims to increase flexibility in task allocation, optimize time management, and improve workstation utilization to enhance the efficiency of the production process. This study aims to optimize working time on the product workstation track using Lean concepts for Line Balancing [15]. The observed data pertains to the condition of the production line. Once the necessary data is collected, it will be analyzed using several methods. The research methodology will be discussed further.

This study contributes significantly to the field of industrial engineering by introducing a mathematical modeling approach that integrates lean manufacturing principles with dynamic takt time optimization in single-model assembly line balancing. The novelty lies in the incorporation of flexible task assignments, which allows for more adaptive and efficient production scheduling in response to fluctuating customer demand and varying process capacities. These outcomes provide a robust framework for manufacturers seeking to streamline operations, reduce idle time, and minimize the number of operators and machines required, thereby contributing to cost efficiency and operational agility.

Research Methodology

This paper considers three crucial workflow steps to actualize the research as mentioned earlier, as summarized in Figure 6. The first step involves objective research, the second step is model development, and the third step is model solution.

The model formulation includes an objective function aimed at minimizing takt time, along with constraints that account for cycle time, task precedence, and production capacity. Verification was performed through simulation using real production data, ensuring the model's applicability and reliability. Additionally, sensitivity analysis was conducted to evaluate the model’s responsiveness to changes in demand and capacity parameters. This methodological rigor not only validates the model’s effectiveness but also reinforces its adaptability to dynamic production environments.

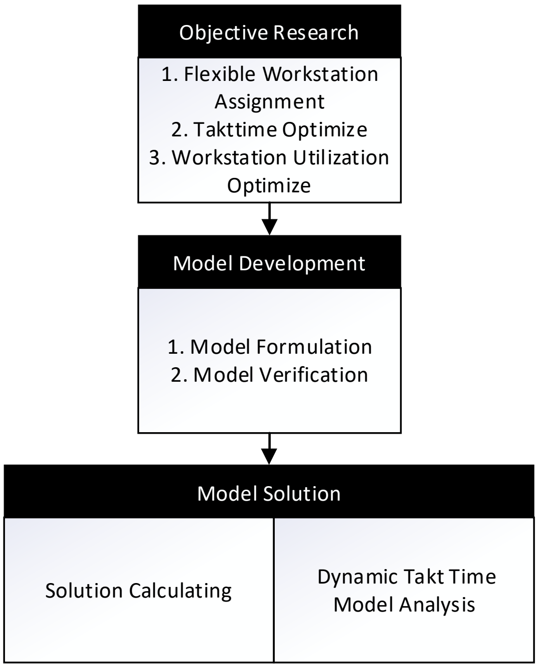

Figure 6. Research methodology

1. The research objectives have been determined based on the problem phenomenon.
2. A mathematical line-balancing model has been formulated by considering the lean concept.
3. The developed mathematical model has been verified, and a solution search has been performed.
4. The model has been analyzed to explore opportunities for maximizing workstation time by applying lean concepts to the line-balancing model.
5. Additionally, sensitivity analysis has been performed on production capacity and demand parameters.

Results and Discussion

Line Balancing

Line balancing is a group of people or machines that carry out sequential tasks in assembling a product given to each resource in a balanced manner in each production line so that high work efficiency is achieved at each workstation. Line balancing is assigning several jobs to workstations related to each other in one track or production line. The workstation has a time that is, at most, the cycle time of the workstation. The function of line balancing is to create a balanced path [16].

In solving line balancing problems, industrial management must know about work methods, equipment, machines, and personnel used in the work process. The data required is information about the time required for each assembly line and the precedence relationship [10][17]. Activities are the arrangement and sequence of various tasks that need to be carried out; industrial management needs to determine the production level per day, which is adjusted to the level of total demand and then divided into the productive time available per day. This result is cycle time, the product time available at each workstation [18][19][20].

There are several steps to solve line balancing problems. The following are the step for solving the problem as follows [2][21][22]:

1. Identify individual tasks or activities to be performed.
2. Determine the time needed to carry out each task.
3. Determine precedence constraints, if any, related to each task.
4. Determine the required output [1] [2]

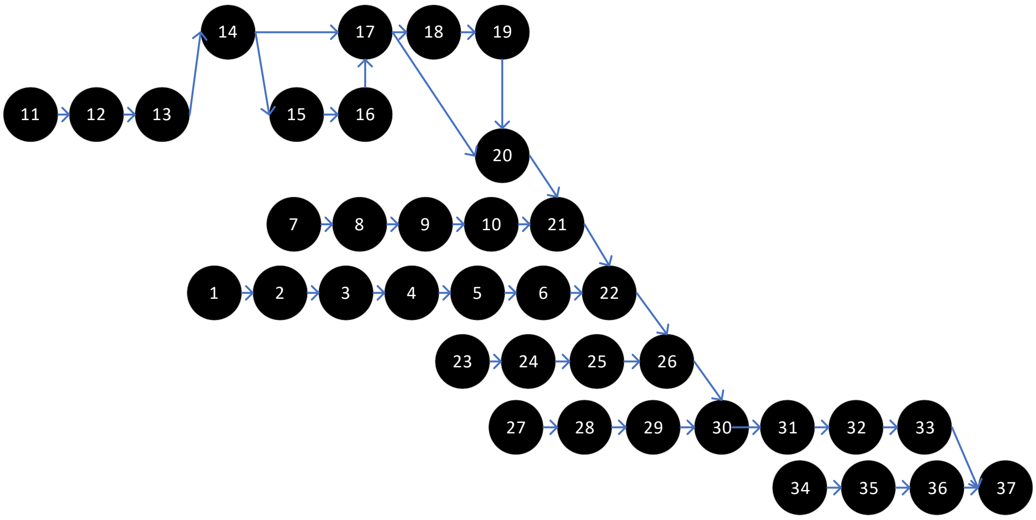

Figure 7. Precedence diagram of production process

Model Development

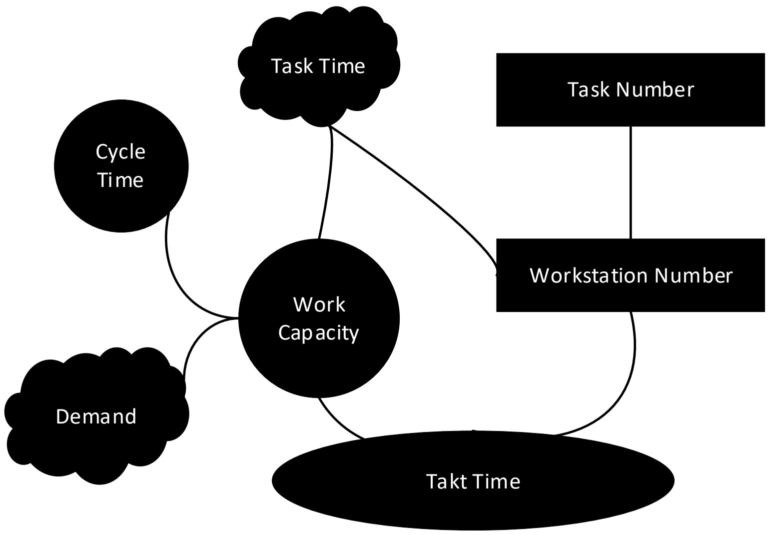

Figure 8. Influence diagram of the problem

The Influence Diagram explains that to optimize the takt time, the processing time in each workstation must be optimized by reviewing the assignment of task and task time. Takt time will be dynamic based on demand and work capacity of production line.

In the mathematical model of the assembly line balancing method, there is an objective function that serves to describe the objectives of the study and a constraint function that serves to describe the limitations, namely:

1. Objective Function

   To optimize the workstation from the specified Takt Time. The decision variable for this research model is minimizing takt time.

$$Min\ Z = \sum_{k=1}^{K} TkT_{ik} \quad (1)$$

2. Takt time calculation

   To reduce inventory levels, the production flow only makes the required amount based on takt time. Apart from that, to determine the production rhythm, takt time is needed, which regulates the rate at which each workstation works. This takt time is a reference for how fast the production line must work to meet demand. The amount of Talk time is obtained from work capacity divided by lot production size.

$$TkT = \frac{WC}{Q} \quad (2)$$

3. Constraint
For each task X, there must be one assigned station. The assignment constraint function with task i can only be assigned to one workstation.

$$\sum_{k=1}^{K} X_{ik} = 1, \qquad i = 1,2, \dots, n \quad (3)$$

4. The constraint function guarantees that the total task time assigned to workstation i does not exceed Takt Time. For each station, the total time for the assigned tasks must be less than the maximum Takt time.

$$\sum_{k=1}^{K} (t_i \; x \; X_{ik}) \leq TkT, \quad k = 1,2, \dots, k \quad (4)$$

5. Precedence constraints.
For each precedence pair, the predecessor task i cannot be assigned to a later station than its successor task j. The constraint function ensures that if task i is assigned to workstation j, its value is set to 1, otherwise it is set to 0.

$$\sum_{k=1}^{K} (KX_{jk} - KX_{jk}) \geq 0, \quad (i,j) \in Pred \quad (5)$$

6. The constraint function ensures that if task i assigned to workstation j, the frequency is set to 1, otherwise it is set to 0.

$$X_{ij} = 0, or\ 1 \quad (6)$$

$$Y_{ij} = 0, or\ 1 \quad (7)$$

7. Takt Time must be greater than cycle time for steady state assumptions.

$$TkT \geq CYCTIME \quad (8)$$

8. The Y(i,j) assignment variables are binary integers.

$$Y_i \in \{0,1\} \quad \forall\, i = 1 \dots k \quad (9)$$

Model Notation
The notation used in this model is as follows:

i	Workstation, i = 1...k
D	Demand. (unit/period)
M_i	Workstation Location
N	Number of Workstation.
WC	Work Capacity (time/period)
CYCTIME	Cycle Time (time/unit)
TkT	Takt time (time/unit)
t	Task time at Workstation M_i. (time/unit)
Q	Lot production size. (product/unit)
Y	Binary Variable
X	Task Assigned in Workstation

System Assumptions

The assumptions used in this model are (1) The ability of the workstation to work is greater than the total arrival rate of product raw materials so that the production flow is in a steady state condition. (2) The raw materials used in the production flow are always available. (3) If there is a buildup of products waiting to be processed in front of the workstation, the buffer capacity is unlimited. (4) Each workstation starts the following process when ready, with products in the buffer. (5) The operation time at each workstation follows the takt time, so the takt time must be greater than the cycle time.

Result and Analysis

After conducting simulations using the proposed model, the results obtained align with Table 1

Table 1. Result

Workstation	*Task Number*	Cycle Time	∑Cycle Time	Takt Time
Workstation 1	1	2	10	10
	2	1		
	3	2		
	4	2		
	5	3		
Workstation 2	7	2	9	10
	8	2		
	9	2		
	10	2		
	11	1		
Workstation 3	12	2	10	10
	13	2		
	14	1		
	15	2		
	16	1		
	17	2		
Workstation 4	6	1	10	10
	18	2		
	19	1		
	20	2		
	21	2		
	22	2		
Workstation 5	23	1	10	10
	24	1		
	25	2		
	26	1		
	27	1		
	28	1		
	29	1		
	30	2		
Workstation 6	31	2	9	10
	32	1		
	33	1		
	34	1		
	35	1		
	36	1		
	37	2		
Total			58	60

By combining processes and minimizing trajectories, it has an impact on optimizing working time in the unit assy process. The performance results of Line Balancing are listed in the table below.

Table 2. Performance Result

Performance Indicator	After
Workstation Number	6 WS
Line Efficiency	96,66%
Balance Delay	3,33%
Smoothness Index	98,77%

Conclusion

Based on research, modeling, and calculation results, the Cycle Time obtained is no more than the takt time required for each process. Combining the process and minimizing the path can optimize the time used by Line Efficiency to 96,66%. Balance delay becomes 3,33%, and smoothness index is 98,77%. So, the suggestion from the conclusion is based on the proposed model using a lean technique, which generates, as possible solutions, only partitions of the task set that meet the precedence constraint. Combine processes on the unit assembly line to optimize working time and reduce operator loss and waiting times. This impacts production lines because it can reduce the number of operators and machines used.

Limitations the current study assumes are unlimited buffer capacity and constant availability of raw materials, which may not reflect real-world constraints. Furthermore, the model is applied to a single-model assembly line, limiting its generalizability to more complex, mixed-model environments. Future research could extend this work by incorporating stochastic elements such as machine breakdowns, variable task times, and multi-model production scenarios. Additionally, integrating real-time data analytics and machine learning techniques could enhance the model's predictive capabilities and responsiveness, paving the way for more intelligent and autonomous production systems.

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