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Strategic Line Balancing for Enhanced Efficiency in Solar Module Manufacturing: A Comprehensive Study in the Renewable Energy Sector

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A B S T R A C T

This study endeavors to enhance the productivity of solar module production in a renewable energy conversion company. The existing production line needs help in achieving the daily target of 64 units, resulting in an actual output of only 40 units. This study focuses on optimizing the production line by considering processing time adjustments and operator flexibility. To accurately measure working time, we incorporate operator flexibility and adjustment factors in the planning phase of solar module production. The primary objective is establishing an optimal production trajectory by balancing the load and capacity across workstations, thereby elevating overall production efficiency. The approach involves the application of the trial-error method and the shortest operation time method, implemented through POM QM software. Through meticulous data analysis, we determine that the trial-error process yields the most optimal results. Post-implementation, improvements are evident as the solar module production capacity increases to 60 units per day from the initial 40 units. Additionally, the idle time ratio on the assembly line to available time diminishes to 13.17% after optimization. This study contributes valuable insights into the effective enhancement of solar module production lines, emphasizing practical methodologies and software-assisted techniques for achieving substantial productivity gains in the renewable energy sector.

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1. INTRODUCTION

Production planning has an essential role in an industry (Imansuri et al., 2024). Production planning involves production scheduling, especially in the arrangement of operations or work assignments to be carried out (Bueno et al., 2020). Production planning is continuous, meaning it needs to be evaluated continuously because an efficient production line is needed (Boysen et al., 2022; Swangnop et al., 2019). Inappropriate production planning can result in capacity and efficiency problems in the production line. This inaccuracy can cause problems such as material constraints, high delay times, and many idle operators due to unbalanced workloads. Therefore, balancing the production line can provide the same output from each workstation (Albus & Seeber, 2023; Katiraee et al., 2021). The goal of production line balancing is the assignment of activities to workstations by optimizing certain objective functions, such as maximizing worker utilization or minimizing cycle times. The main objective of the production line balance analysis is to balance the workload at each workstation (Lingitz et al., 2019).

PT Winnar is a company that converts new renewable energy sources, such as solar modules. The company's production planning problem is that the operating time for each work element has yet to be calculated based on standard time. So, the production planning is less accurate because the calculation of the time needed to complete one production cycle needs to consider adjustment factors (internal operators) and inclusion factors (external operators). So it will affect productivity and the balance of all production. Productivity parameters include bottleneck time, line efficiency, throughput (capacity), production time, and production costs. In addition, the company still needs to set a daily production target. Currently, the daily production target is only based on the length of production time for lamination work elements, namely 64 units per day.

Meanwhile, based on the results of observations, there is a higher workstation processing time than the laminate workstation. As a result, the solar module production target has yet to be achieved, which is currently only 40 units per day. Therefore, it is necessary to increase production capacity by analyzing the balance of the production line. This study begins with measuring working time by considering the operator's flexibility and adjustment factors in planning the production of solar modules. Production line balance analysis aims to create an optimal production line, balance load and capacity between workstations, and increase production productivity.

2. LITERATURE REVIEW

Line balancing is a method of increasing the efficiency of workstations in the production process path so that one or more operators handling each workstation have a workload (working time) that does not exceed the cycle time of that workstation (Sulistyo, 2022). The line balancing concept aims to obtain a minimum balanced delay/idle time value and maximum efficiency (Ozan Yilmazlar et al., 2020). Combining several operational elements is carried out at several workstations to achieve high work efficiency and obtain the lowest possible delay/idle ratio at each workstation (Tuba & Arslankaya, 2023). Several methods are used to balance the production line, including designing a mixed integer linear programming (MILP) mathematical model (Diaz et al., 2022; Lingitz et al., 2019; Lopes et al., 2021; Navas-Barrios et al., 2022), building a simulation model using a discrete event simulation approach and mixed integer programming (Ibriksz et al., 2020; Rocha & Lopes, 2022), and a combined approach to integer programming and metaheuristic mathematical methods (Ozan Yilmazlar et al., 2020). In addition, the lean concept approach is also applied to the problem of balancing the motherboard production line in the electronics sector (Vijay & Gomathi Prabha, 2019). Another study found that line balancing with a heuristic approach using the ranked positional weight method and the largest candidate techniques in the garment industry increased production line efficiency by 76.45% (Manaye, 2019). One of the methods used to solve production line balance problems is the heuristic method. The heuristic method is used to create a strategy because of involvement, instinct, or the correct standard to obtain a better setting than the setting that has just been achieved. This method involves using knowledge and experience to make decisions that are not optimal but are efficient. Examples of heuristic methods in line balancing are the trial error method, shortest operation time, largest candidate time, and ranked positional weight (Basuki & Cahyani, 2020; Faqih Mujahidulloh & Oec Arfan Bakhtiar, 2021).

3. RESEARCH METHOD

Preliminary studies have been carried out in field studies and literature studies. Problem identification and problem formulation are

obtained based on field studies that have been carried out. Meanwhile, literature studies were conducted to obtain previous theories and research. Risk identification is carried out first to determine the risks that might occur in a job. The data collection process is carried out by observing the work performed by the operator. The measurement of working time is done directly by the stopwatch method.
Data processing is done by calculating the standard time after the data is declared sufficient and uniform. Calculation of the balance of the actual and proposed production paths is carried out to obtain improvements to the production path by comparing the trial-error method, ranked position weight, longest operation time, and shortest operation time. The calculation of production line balance for the Shortest Operation Time methods uses the POM QM software.

4. RESULT AND DISCUSSION

The first step in data collection is to determine the elements of work on the solar module production line and operator data along with working hours in Table 1.

Table 1. Work elements on the solar module production line

Work Station	Work Element	Total work stations (tracks/shift)	Number of Operators per Shift	Working Hours per Shift (Seconds)	Number of Shifts per Day
Cutting Process	Interconnector Cut Immersion in flux Interconnector Drying	2	1 work station = 1 Operator	28,800	1
Single Solder	Soldering the Positive Pole Interconnector on the solar cell	8	1 work station = 1 Operator	28,800	1
Solder on Series	Arranging Cells into a series Soldering the negative pole interconnector on the solar cell	6	1 work station = 1 Operator	28,800	2
Assembling	Cutting TPT Cutting EVA Arranging Cell Series into modules Soldering the PV Ribbon to the module Assemble EVA, TPT, modules and glass Connect test	2	1 work station = 2 Operator	28,800	2
Lamination process	The lamination process uses the oven	2	1 Shift = 2 Operator	28,800	2
Inspection	Specification test (EL Tester) Installation of data stickers and barcodes	1	1 Operator	28,800	2
Finishing	Framming Installation of junction boxes Finishing Packing	1	3 Operator	28,800	2

Standard Time Calculation

Data was collected directly on each work element with as many as 30 observations to obtain the average cycle time for each work element. Data testing has been carried out on the cycle time of each work element using data adequacy tests and data uniformity tests. Based on the results of the adequacy test, all work elements have a sufficient number of data samples (N' < N). Meanwhile, based on the data uniformity test, all data is uniform, so no data is outside the upper and lower control limits. Before calculating the normal time and standard time, each operator's adjustment factor and allowance factor must first be determined. The method for determining the adjustment value in this study uses the Westinghouse method. Table 2 is a recapitulation of the normal time and standard time calculation and the determination of adjustment factors and allowances for each work element.

Table 2. Recapitulation of normal time, standard time and determination of adjustment factors and allowances

Work Element	Uniformity test	Adequacy test	Cycle time (seconds)	Adjustment Factors	Normal time (seconds)	Allowances	Standard time (seconds)
Interconnector Cut	Uniform data	N' < N. 5.983 < 30	53.525	1.140	61.019	0.125	68.646
Immersion in flux	Uniform data	N' < N. 21.107 < 30	21.924		24.993		28.118
Interconnector Drying	Uniform data	N' < N. 0.325 < 30	296.978		338.555		380.874
Soldering the Positive Pole Interconnector on the solar cell	Uniform data	N' < N. 0.003 < 30	2585.808	1.050	2715.098	0.195	3244.543
Arranging Cells into a series	Uniform data	N' < N. 0.049 < 30	608.326	1.080	656.992	0.195	785.106
Soldering the negative pole interconnector on the solar cell	Uniform data	N' < N. 0.002 < 30	3756.55		4057.074		4848.203
Cutting TPT	Uniform data	N' < N. 2.821 < 30	53.325	1.100	58.658	0.225	71.855
Cutting EVA	Uniform data	N' < N. 1.545 < 30	106.65		117.315		143.711
Arranging Cell Series into modules	Uniform data	N' < N. 0.024 < 30	725.96		798.556		978.231
Soldering the PV Ribbon to the module	Uniform data	N' < N. 0.114 < 30	315.821		347.403		425.569
Assemble EVA, TPT, modules and glass	Uniform data	N' < N. 0.307 < 30	272.549		299.804		367.260
Connect test	Uniform data	N' < N. 0.676 < 30	83.287		91.616		112.229
The lamination process uses the oven	Uniform data	N' < N. 0.004 < 30	1800	1.000	1800.000	0.0625	1912.500
Specification test (EL Tester)	Uniform data	N' < N. 0.032 < 30	625.5	1.000	625.500	0.0625	664.594
Installation of data stickers and barcodes	Uniform data	N' < N. 1.188 < 30	94.901		94.901		100.832
Framming	Uniform data	N' < N. 0.066 < 30	424.22	1.07	453.915	0.2350	560.586
Installation of junction boxes	Uniform data	N' < N. 0.372 < 30	121.34		129.834		160.345
Finishing	Uniform data	N' < N. 0.068 < 30	342.752		366.745		452.930
Packing	Uniform data	N' < N. 0.550 < 30	186.12		199.148		245.948

Calculation of actual production line balance.

The actual production line balance calculation is carried out after obtaining the standard time for each work element. In the balance of production lines, the amount of delay and idle time indicates that a line still needs to be balanced because it results in buildup or emptiness in a workstation. Delay is the waiting time for material before processing, while idle is the waiting time of the operator. Delay and idle time data can be seen in Table 3.

Table 3. Data delay and idle time per work station

Work Station	Process time (seconds)	Delay	Idle
Cutting Process	238.819	0.000	0.000
Single Solder	405.568	166.749	0.000
Solder on Series	938.885	533.317	0.000
Assembling	1049.428	110.543	0.000
Lamination process	956.250	0.000	93.178
Inspection	765.426	0.000	190.824
Finishing	1419.808	654.382	0.000
Total		1464.991	284.002
Total delay time		**1748.99 seconds**	

Production capacity per workstation can be calculated by dividing the total working hours by the processing time of each workstation. The calculation of production capacity per workstation can be seen in Table 4.

Table 4. Calculation of production capacity per work station

Work station	Process time (seconds)	Working Hours per Shift (Seconds)	Number of Shifts	Production Capacity (Units/Day)
Cutting Process	238.819	28,800	1	120.6
Single Solder	405.568	28,800	1	71
Solder on Series	938.885	28,800	2	61.3
Assembling	1049.428	28,800	2	54.9
Lamination process	956.250	28,800	2	60.2
Inspection	765.426	28,800	2	75.3
Finishing	1419.808	28,800	2	40.6

Calculation of the actual production line capacity for each day can be calculated using the formula:

$$\text{Working Hours per Shift x } \frac{\text{Number of Shifts per day}}{\text{largest workstation processing time}} =$$

$$28800 \text{ x } \frac{2}{1419{,}808} = 40 \text{ units/day}$$

The production cost of the proposed production line is calculated by calculating the monthly output for 22 working days of 880 units. The direct labor cost per unit is IDR 174,644 (Regional Minimum Wage Kab. Bogor 2023). The production process time per unit of the production line was 1,440 seconds, with 16 working hours daily. Efficiency calculations are performed for each workstation and production line in Table 5.

Table 5. Calculation of production efficiency per work station

Work station	Process time Wi (seconds)	Ws (seconds)	Workstation efficiency (%)
Cutting Process	238.819	1419.808	16.820
Single Solder	405.568		28.565
Solder on Series	938.885		66.128
Assembling	1049.428		73.913
Lamination process	956.250		67.351
Inspection	765.426		53.911
Finishing	1419.808		100.000
Total	**5774.183**		

$$\text{Production Line Efficiency} = \frac{\sum_{i=1}^{n} W_i}{n\,W_s} \text{ x } 100\%$$

$$= \frac{5774{,}183}{7 \ x\ 1419{,}808} \text{ x } 100\% = 58.1\ \%$$

The balance delay is the ratio between the idle time in the assembly line and the available time. The balance delay calculation is as follows:

$$= \frac{n\,W_s - \sum_{i=1}^{n} W_i}{n\,W_s} \text{ x } 100\%$$

$$= \frac{7 \text{ x } 1419.808 - 5774.183}{7 \text{ x } 1419.808} \text{ x } 100\% = 0.419 = 41.9\%$$

Calculation of proposed production line balance.

After processing the data and getting results from the current solar module production path balance, the next stage is to calculate improvements to the balance of the production path to obtain a better production system. The corrective steps taken are as follows:

1) Trial Error Method

Step 1: Determine the processing time

Actual processing time = largest work element processing time = 1912.5 seconds.

Rearrange the work elements for each workstation, human resources, and the number of production passes within the workstation by trial and error. Calculate the standard time per workstation in Table 6.

Table 6. The rearrangement of work stations

Work stastion	Work element	Total work stations per shift	Operating time of each workstation per Shift	Total Standard Time (Seconds)
Cutting Process	Interconnector Cut	1	68.646	693.20
	Immersion in flux		28.118	
	Interconnector Drying		380.874	
	Cutting TPT		71.855	
	Cutting EVA		143.711	
Single Solder	Soldering the Positive Pole Interconnector on the solar cell	4	927.012	927.01
Solder on Series	Arranging Cells into a series	6	130.851	938.88
	Soldering the negative pole interconnector on the solar cell		808.034	
Assembling	Arranging Cell Series into modules	2	489.116	941.64
	Soldering the PV Ribbon to the module		212.784	
	Assemble EVA, TPT, modules and glass		183.630	
	Connect test		56.115	
Lamination process	The lamination process uses the oven	2	956.250	956.25
Inspection	Specification test (EL Tester)	1	664.594	765.43
	Installation of data stickers and barcodes		100.832	
Framing	Framming	1	560.586	720.93
	Installation of junction boxes		160.345	
Finishing	Finishing	1	452.930	698.88
	Packing		245.948	

Calculating delay and idle time

The delay and idle time for solar module production by improving the production line balance using the trial-error method can be seen in Table 7.

Table 7. Delay and idle time per work station

Work Station	Process Time (seconds)	Delay	Idle
Cutting process	693.204	0	0
Single solder	927.012	233.808	0
Solder on series	938.885	11.873	0
Assembling	941.644	2.759	0
Lamination process	956.250	14.606	0
Inspektion	765.426	0	190.824
Framming	720.930	0	44.496
Finishing	698.878	0	22.052
Total		263.046	257.372
Total delay time		**520.42 seconds**	

Calculate the capacity per work station.

The calculation of production capacity per workstation can be seen in Table 8.

Table 8. Calculation of production capacity per work station

Work Station	Process time (seconds)	Working Hours Per Shift (seconds)	Number of Shifts Per Day	Production Capacity (Unit/Day)
Cutting process	693.204	28,800	2	83
Single solder	927.012	28,800	2	62
Solder on series	938.885	28,800	2	61
Assembling	941.644	28,800	2	61
Lamination process	956.250	28,800	2	60
Inspection	765.426	28,800	2	75
Framming	720.930	28,800	2	79
Finishing	698.878	28,800	2	82

Calculation of production line capacity per day.

Work Hours Per Shift x Number of Shifts/processing time of the largest workstation = 57600 x 2 / 956.25 = 60 units / day. The production cost of the proposed production line is calculated by obtaining monthly output for 22 working days of 1,320 units. Direct labor costs per unit are IDR 116,429 (Regional Minimum Wage Bogor Regency 2023). The production process time per unit of the production line is 960 seconds, with 16 working hours daily.

Calculation of efficiency per work station.

Efficiency calculations carried out for each workstation can be seen in Table 9.

Table 9. Calculation of production efficiency per work station

Work Station	Wi (seconds)	Ws (seconds)	Workstation efficiency (%)
Cutting process	693.204	956.250	72%
Single solder	927.012		97%
Solder on series	938.885		98%
Assembling	941.644		98%
Lamination process	956.250		100%
Inspection	765.426		80%
Framming	720.930		75%
Finishing	698.878		73%

Production line efficiency calculation.

The efficiency calculations carried out for the solar module production line can be seen in Table 10.

Table 10. Production Line Efficiency Calculation

Work Station	Wi (seconds)	Ws (seconds)	Production Line Efficiency (%)
Cutting process	693.204	956.25	86.80%
Single solder	927.012		
Solder on series	938.885		
Assembling	941.644		
Lamination process	956.250		
Inspection	765.426		
Framming	720.930		
Finishing	698.878		
Total	**6642.230**		

$$\text{Production Line Efficiency} = \frac{\sum_{i=1}^{n} W_i}{n\, W_s} \text{ x } 100\% = \frac{6642{,}23}{8 \text{ x } 956{,}25} \text{ x } 100\% = 86{,}8\%$$

Balance delay calculation

$$= \frac{n\, W_s - \sum_{i=1}^{n} W_i}{n\, W_s} \text{ x } 100\%$$

$$= \frac{8 \text{ x } 956.25 - 6642.23}{8 \text{ x } 956.25} \text{ x } 100\% = 0.1317 = 13.17\%$$

2) Shortest Operation Time Method

Calculate production line balance using the shortest operation time method using POM-QM software. The cycle time for the shortest operation time method determined is the largest operating time, namely 4848 seconds. Table 11 shows that the trial-and-error method is the best method for implementing a balanced production path for solar module products. It has the shortest idle time of 520.42 seconds and the highest output capacity of 60 units per day.

Table 11. Selected production line balancing method

Comparative Aspects	Actual Assembly Track	Proposed Assembly Path	
		Trial Error	Shortest Operation Time
Delay time (seconds)	1748.99	520.42	14178
Assembly Line Efficiency	58.10%	86.80%	83.75%
Output (Units/day)	40	60	24
Production time (seconds)	1440	960	73086
Cost of Production (Direct Labor Cost)	IDR 119,800	IDR 79,900	IDR 291,074
Number of Workstations	22	18	18
Balance Delay	41.9%	13.17%	16.25%

Figure 1 shows the processing time at each workstation using the trial-and-error method.

When compared with Figure 2, which is a diagram of the time per workstation using the shortest operation method, it can be concluded that by using the trial-and-error method, the processing time at each workstation tends to be balanced; only at the workstation at the beginning and end does the processing time tend to be fast. However, using the shortest operation method, the processing time fluctuates extremely at the 13th and 18th workstations. Therefore, the selected production line balance method is the trial-and-error method, with an increased line efficiency of 86.80%.

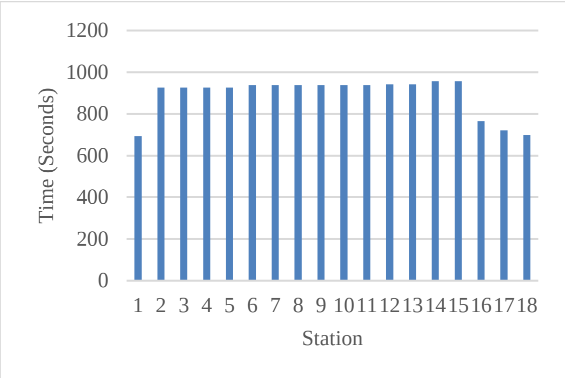

Figure 1. Time per station using trial error method

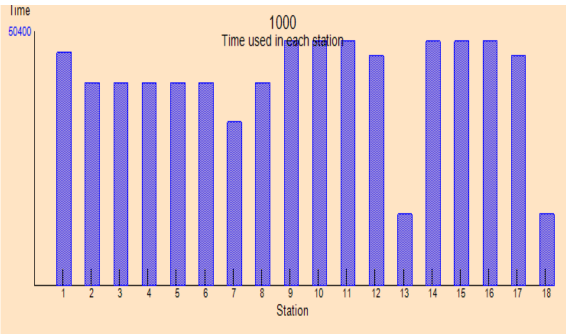

Figure 2. Time per station using shortest operation method with POM QM software

5. CONCLUSION

The recommendation for improvement of the solar module production line is to use the trial-error method. Based on the results of data analysis and processing, it was found that the production of solar modules increased to 60 units per day with a processing time of 960 seconds per unit. Production costs based on employee wages incurred by the company are cheaper than the initial conditions. Moreover, there is a reduction in workstations from 22 to 18 workstations. The ratio between idle time on the assembly line and available time decreased to 13.17% after the repair. Further improvements are needed to evaluate production trajectories and increase daily production targets. Further research can be carried out using simulation and mathematical models of solar module production lines to streamline time, workload, and production costs.

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