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A Simulation-Driven Study of Bottleneck Reduction in Crude Palm Oil Production Using Arena Software

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Abstract

Productivity is determined by output within the production process and is achieved through a combination of effectiveness, doing the right things, and efficiency, doing things correctly. In the context of the issues faced, bottlenecks impact productivity primarily due to two factors: worker scheduling and the method used to identify the bottleneck. The objectives of this study are to determine the root cause of bottlenecks related to worker schedules, identify other critical bottlenecks using Arena simulation, and propose solutions to address these constraints. Arena simulation was employed due to its cost-effectiveness compared to alternative methods. Production data were collected through interviews, direct observation and time study. Key findings revealed that improper worker allocation led to delays in critical processes, notably the deliver to oil room process. Simulation results showed that optimising worker schedules and increasing resource capacity effectively reduced production cycle times. This study highlights the value of simulation tools as a cost-efficient approach for identifying and resolving bottlenecks, ultimately supporting enhanced productivity within manufacturing systems.

1. Introduction

Crude palm oil (CPO) production stands as a cornerstone of the global edible oil industry, with Southeast Asia particularly Malaysia and Indonesia accounting for over 85% of the world's supply. The sector's economic, social, and environmental significance is profound: it supports millions of livelihoods, underpins rural development, and is increasingly scrutinized for its sustainability practices and environmental footprint. The operational complexity of palm oil mills arises from the need to process large volumes of fresh fruit bunches (FFB) within tight timeframes to preserve oil quality, all while managing resource constraints, fluctuating input quality, and stringent environmental regulations. Achieving high productivity and sustainability in this context is both a technical and managerial challenge, as mills must continuously optimize throughput, minimize waste, and ensure compliance with evolving standards for sustainable palm oil production (Chew *et al.*, 2021; Hasanudin & Setiadi, 2016; Sembiring & Imam Ramzani, 2020; Shukri *et al.*, 2020).

Despite technological advancements, crude palm oil mills frequently encounter persistent productivity challenges. These include equipment downtime, process inefficiencies, labour shortages, and variability in FFB quality. Such issues are exacerbated by the sequential and interdependent nature of palm oil processing stages namely sterilization, threshing, pressing, clarification, and kernel recovery, where a single underperforming process can constrain the entire system. This phenomenon, known as a bottleneck, directly limits overall throughput and operational efficiency. Bottlenecks manifest as excessive waiting times, resource underutilization, and increased operational costs, making their identification and mitigation a critical priority for mill managers. Systematic bottleneck analysis, therefore, is essential for diagnosing root causes, prioritizing interventions, and achieving sustainable productivity improvements (Herrera-Uribe *et al.*, 2023; Lestari *et al.*, 2018; Mahmoodi *et al.*, 2022; Mardono *et al.*, 2019; Martin & Wainer, 2024).

The theoretical underpinnings of bottleneck analysis are deeply rooted in the Theory of Constraints (TOC) and lean manufacturing principles. TOC posits that every production system is limited by at least one constraint, and that targeted improvement of this constraint yields the greatest impact on overall performance. Lean manufacturing, meanwhile, emphasizes the elimination of waste and continuous flow, advocating for systematic identification and removal of process inefficiencies. Over time, bottleneck analysis has evolved from traditional, experience-based methods to data-driven and simulation-based approaches. These modern methodologies leverage real-time shop floor data, machine learning, and artificial intelligence to dynamically identify, predict, and mitigate bottlenecks, especially in complex and variable production environments. The integration of Industry 4.0 technologies such as digital twins and sensor networks can further enhance the ability to monitor, analyse, and optimize production systems in real time (Chen *et al.*, 2023; Mahmoodi *et al.*, 2022; Martin & Wainer, 2024; Sevella *et al.*, 2025; Skoogh *et al.*, 2023).

Simulation, particularly discrete event simulation (DES), has emerged as a powerful tool for modelling and optimizing industrial processes. By creating a virtual representation of the production system, simulation enables practitioners to experiment with different configurations, test "what-if" scenarios, and evaluate the impact of process changes without disrupting actual operations. This approach is especially valuable in environments where direct experimentation is costly, risky, or impractical. Simulation facilitates the identification of bottlenecks, quantifies their impact on key performance indicators (KPIs) such as throughput and equipment utilization, and supports data-driven decision-making for process improvement. The ability to integrate real-time data and optimization algorithms further extends the utility of simulation in dynamic and uncertain production contexts (Markovitch & Profozich, 1996; Neeraj *et al.*, 2018; Sevella *et al.*, 2025; Sinthamrongruk *et al.*, 2019).

Arena simulation software is widely recognized for its robust capabilities in discrete event simulation and industrial process modelling. Its graphical, object-oriented interface allows users to construct detailed models of production systems, incorporating machines, operators, material flows, and control logic. Arena supports integration with optimization algorithms such as genetic algorithms and lean tools, to enable users to identify bottlenecks, evaluate alternative process configurations, and optimize scheduling and resource allocation. Key features include scenario analysis, performance measurement, and the ability to model both discrete and continuous processes. Arena's modular architecture and open design facilitate customization and scalability, making it suitable for a broad range of applications in manufacturing, logistics, and agro-industrial sectors. Its proven track record in supporting productivity improvement and process reengineering underscores its value as a decision-support tool for both researchers and practitioners (Hammann & Markovitch, 1995; Hussein *et al.*, 2009; Markovitch & Profozich, 1996; Neeraj *et al.*, 2018; Sinthamrongruk *et al.*, 2019).

The application of simulation techniques, including Arena, to palm oil processing and similar agro-industrial systems has gained momentum in recent years. Case studies demonstrate the effectiveness of simulation in identifying bottlenecks such as sterilization and sorting processes to quantifying their impact, and evaluating process improvement strategies. For example, Arena-based models have been used to simulate mechanized equipment operations in Malaysian palm oil mills, revealing that targeted interventions in bottleneck areas can yield significant gains in throughput and resource utilization. Simulation also serves as a test bed for capacity expansion scenarios, process reengineering, and the integration of new technologies, thereby reducing implementation risks and supporting evidence-based decision-making. Despite these successes, the literature reveals a gap in the systematic application of advanced simulation tools like Arena in the palm oil sector, particularly in integrating real-time data and optimization frameworks (Ahmarofi *et al.*, 2024; Mohd-Lair, Chan, *et al.*, 2012; Mohd-Lair, Lee, *et al.*, 2012; Owolarafe & Oni, 2011).

While simulation-based bottleneck analysis is well established in manufacturing, its application in crude palm oil processing remains limited and fragmented. Most existing studies focus on isolated process improvements or use generic simulation tools without fully leveraging the advanced capabilities of platforms like Arena. There is a pressing need for comprehensive, validated simulation models that reflect the unique operational realities of palm oil mills, incorporate real-time data, and support integrated optimization of productivity, cost, and sustainability outcomes. The present case study addresses this gap by demonstrating the use of Arena simulation software for detailed bottleneck analysis and productivity improvement in a crude palm oil processing mill. By bridging theoretical frameworks with practical insights, this work aims to provide a replicable methodology for process optimization in agro-industrial contexts, contributing to both academic research and industry practice (Agrawal & Dhamija, 2023; Ahmarofi *et al.*, 2024; Chen *et al.*, 2023; Mahmoodi *et al.*, 2022).

The identified company produces crude palm oil as its main output, yet production performance remains unstable due to inefficiencies along the processing line. According to the Mill Manager, Mr Yong, one major issue relates to improper worker scheduling. The current bottleneck has not been fully optimised, and this condition is associated with work timetable arrangements and limited multi-skilling among operators. Workers are assigned to specific stations that require particular technical competencies to supervise machines. However, when a required operator is absent, no immediate replacement with similar capability is available. This situation disrupts process continuity and reduces overall throughput. Another concern involves the absence of a systematic approach to identify bottlenecks within the production system. Crude palm oil processing still depends on manual monitoring to ensure smooth machine operation and prevent interruptions. Certain stations have limited manpower, and when monitoring demand increases, congestion may occur. Without a structured method for detecting bottlenecks, production delays and capacity loss may continue.

Therefore, this study aims to utilise Arena simulation to model the production system of a CPO processing mill, identify critical bottlenecks, and evaluate alternative workforce scheduling configurations. By simulating different labour allocation strategies and multi-skilling scenarios, the study seeks to propose practical improvements that enhance throughput and operational productivity.

2. Methodology

2.1 Data Collection

Data collection in this study was conducted through interviews and direct observation to obtain relevant operational information. Qualitative approaches were selected because these methods provide detailed and context specific understanding of production activities. Prior to the interview session, a structured list of key questions was prepared to ensure systematic discussion and consistency in data gathering as tabulated in Table 1. An interview was first carried out with the mill manager before the observation of the CPO production line. The discussion covered several important aspects of the manufacturing operation, including the main product, overall process flow, and current performance indicators used to measure efficiency. Additional questions addressed the existing approach for detecting and managing bottlenecks, availability of historical production records, potential constraint areas within the line, and any previous analysis related to bottleneck identification. Information regarding operational limitations, resource distribution, and methods used to determine workflow arrangements was also obtained during the session.

Table 1 *Interview questions*

No	Question	Answer
1	What constitutes the primary product manufactured by the company?	
2	What key performance indicators are applied to evaluate the production process on a daily, weekly, or monthly basis, and whether the established targets are consistently achieved?	
3	What methods or metrics are utilised to assess overall production performance?	
4	Are there any bottleneck conditions within the production line that negatively influence productivity?	
5	What procedures or techniques are implemented to detect and determine bottleneck locations in the system?	
6	What corrective actions or improvement strategies are considered to address the identified bottleneck issues?	

Following the interview, on site observation was performed to gain direct understanding of the production environment. By examining each workstation and process sequence, clearer insight into actual operational practices was achieved. This approach supported verification of interview responses and reduced possible inaccuracies in interpretation. A time study was also conducted to collect quantitative data required for simulation modelling (Fig. 1). The standard processing time for each activity in the crude palm oil production line was recorded, together with the number of workers assigned at each station. These data served as essential input parameters for subsequent analysis using simulation techniques.

No.	ELEMENT DESCRIPTION		READINGS										Total/					
			1	2	3	4	5	6	7	8	9	10	CYCLE	AVG	PR	NT	ALLW	ST
1		R																
		A																
2		R																
		A																
3.		R																
		A																
4		R																
		A																
5		R																
		A																
6		R																
		A																
7		R																
		A																
															TOTAL			

Fig. 1 *Time study sheet*

2.2 Data Analysis

Data analysis refers to the systematic examination of information collected from multiple sources through appropriate analytical procedures. This process includes organised data compilation, documentation, evaluation, and interpretation to address the research objectives and answer defined research questions. Emphasis is placed on maintaining data consistency, dependability, and credibility throughout the analysis stage.

Information obtained from interviews and direct observations was subsequently applied to develop a simulation model of the production line using Arena Simulation software. Arena provides an integrated environment for constructing, evaluating, and improving manufacturing system models. The software supports performance assessment and testing of alternative operational strategies within a controlled virtual setting. The general modelling procedure consists of several structured phases, including system representation, input parameter configuration, model verification, and performance evaluation as illustrated in Fig. 2.

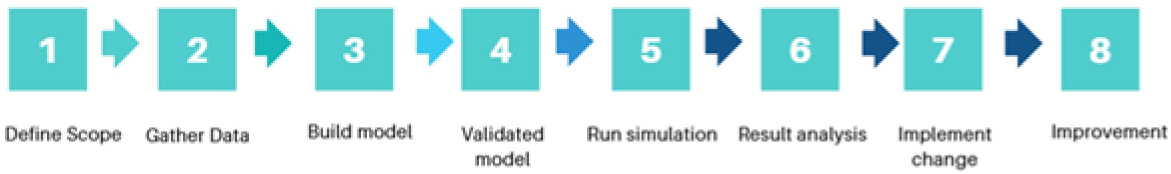

Fig. 2 *Step for Arena simulation*

Based on the assessment of the existing production process, a corrective strategy was formulated to address the identified bottleneck. The proposed improvement was then examined through simulation experiments to determine its practical effectiveness. Model validation was performed by comparing system performance indicators before and after implementation of the suggested changes. Productivity measures derived from both scenarios were analysed to evaluate whether the modification contributed to measurable performance enhancement within the production line.

3. Results and Discussion

3.1 Step 1: Interview and Production Line Observation

In this study, an interview was conducted with a key informant, namely the Mill Manager, to examine the operational process and obtain insights into the CPO production line. The interview provided detailed information regarding the mill layout, workforce structure, and standard operating procedures (SOP). In addition, direct observation was carried out to assess the current CPO process flow, with specific focus on the CPO product. The findings from the observation identified nine workstations involved in the production line process.

3.2 Step 2: Time Study

Files must be During the time study, the processing durations for seven stations were recorded across ten cycles. Based on these measurements, the standard time was determined, as shown in Fig. 3. Referring to the Westinghouse System of Rating, the Production Line Manager evaluated worker performance as follows: good skill (+0.06 C1), average to above-average effort (+0.02 C2), average working conditions (+0.02 C), and average consistency (+0.01 D). The overall performance rating (PR), calculated as presented in Equation 1, was 1.11. A fatigue allowance of 15% was applied.

No.	Element Description		Readings										Total / Cycle	AVG	PR	NT	ALLW	ST
			1	2	3	4	5	6	7	8	9	10						
1	FFB Received and put on Ram	R	28.07	290.05	550.13	815.33	1065.08	1324.17	1586.03	1840.17	2097.13	2355.04	102.29	/4=25.57		28.38		32.64
		A	28.03	28.66	29.74	27.93	25.73	25.05	26.53	23.76	25.81	25.7						
2	Sterilization	R	107.48	370.27	629.49	886.54	1143.21	1404.23	1665.20	1920.30	2179.20	2433.19	558.42	/7=79.77		88.54		101.82
		A	79.41	80.22	79.36	71.21	78.13	80.06	79.17	80.13	80.07	78.15						
3	Threshing station	R	111.23	373.30	634.03	891.02	1147.32	1409.17	1669.32	1923.49	2182.43	2437.21	19.19	/4=4.8		5.33		6.13
		A	3.75	4.03	4.54	4.48	4.10	4.44	4.12	3.19	5.23	4.02						
4	Fill out the digester machine	R	129.40	389.44	655.26	910.38	1169.25	1432.31	1685.29	1942.27	2198.36	2460.42	90.38	/5=24.26	1.11	26.93	15%	30.97
		A	18.17	15.14	21.23	19.36	21.94	23.14	15.97	18.68	15.93	23.21						
5	Digester machine press	R	133.27	393.18	660.17	914.51	1173.46	1435.43	1689.44	1946.59	2202.53	2465.02	24.27	/6=4.05		4.50		5.18
		A	3.87	3.74	4.91	4.13	4.21	3.12	4.15	4.40	4.17	4.6						
6	Delivery to oil room	R	253.20	512.29	780.04	1032.24	1298.14	1552.57	1808.51	2069.53	2322.24	2585.33	718.20	/6=119.7		132.87		152.80
		A	119.93	119.11	119.87	117.73	117.68	117.14	119.07	117.96	119.91	120.31						
7	Oil room start Produce the product	R	261.39	520.39	787.40	1039.35	1299.12	1559.50	1816.41	2071.32	2329.38	2592.07	32.17	4.63		5.14		5.91
		A	8.19	8.1	7.36	7.11	7.98	6.93	7.40	6.79	6.9	6.74						
															TOTAL			**335.45**

Fig. 3 *Time study sheet analysis*

Subsequent analysis generated several findings. Extended completion times observed in certain operations were supported by reasonable justifications. The study primarily examined manual activities, waiting time, and bottlenecks occurring at specific stages of the process. The results indicate that a substantial portion of the production flow depends on manual labour. In addition, manual tasks were found to require longer processing time compared to operations supported by automated equipment.

$$\text{Performance rating (PR)} = 1 + \text{sum of ratings} \quad (1)$$

3.3 Step 3 – Step 6: Identification Bottleneck and productivity of current production process

Table 1 presents an overview of the operating cycle times for each process. The delivery to oil room (Process 6) records the longest average cycle time at 119.7 minutes, making it the most time-consuming operation in the workflow. Sterilisation ranks second with a cycle time of 79.77 minutes, followed by FFB receiving and loading onto the ram at 25.57 minutes. This variation highlights the differing time requirements across production stages. Based on the ranking of operation times, delivery to oil room is placed first, followed by sterilisation, FFB receiving and loading onto the ram, the digester station, the threshing station, the oil room station, and finally the press station. Processes with extended cycle times indicate a higher likelihood of bottlenecks within the system.

Table 1 *Average cycle time and standard time of production line*

Station	Process	Average time (min)	Standard time (min)	Rank
1	FFB received and place on ram	25.57	32.64	3
2	Sterilization	79.77	101.82	2
3	Threshing	4.80	6.13	5
4	Digester	24.26	30.97	4
5	Press	4.05	5.18	7
6	Deliver to oil room	119.7	152.80	1
7	Oil room	4.63	5.91	6

Fig. 4 illustrates the simulation model of the existing crude palm oil production process. According to the time study analysis, the primary bottlenecks are identified at the delivery to oil room process, the sterilisation station, and the FFB receiving and loading stage. Potential improvement measures are discussed in the subsequent section.

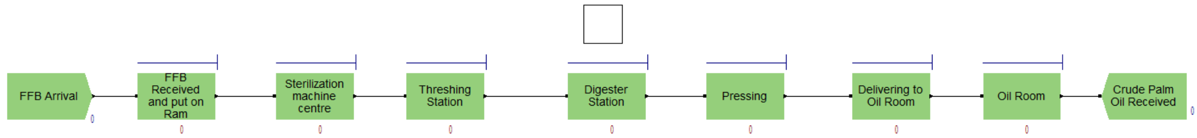

Fig. 4 *Current layout of CPO production line using Arena simulation*

3.4 Step 7: Suggestion of Potential Solution for Improvement

To address the bottlenecks identified in the crude palm oil production line, a set of strategic interventions was proposed, aiming to improve workflow efficiency and overall output. The solutions include increasing resource capacity, streamlining and combining processes, and optimizing the duration of critical operations.

First recommendation is by increasing resource capacity entails allocating additional manpower and equipment to high-demand stages with the longest cycle times, such as the delivery to oil room process (Altendorfer *et al.*, 2021). This approach ensures that sufficient resources are available to meet production requirements and reduce potential delays. Second recommendation is to streamlining operations involves combining related processes (Ruiz-Torres *et al.*, 2019), for example integrating tasks at the digester and press stations, to eliminate redundant transitions and enhance the continuity of the production flow as tabulated in Table 2. This also reduces unnecessary waiting periods and improves overall operational efficiency. Third recommendation is by optimizing process durations focuses on minimizing idle time and enhancing consistency through better scheduling and the adoption of automation technologies (Kelton *et al.*, 2015). Manual tasks can be supported by automated systems to reduce human error, accelerate processing, and improve reliability. Collectively, these interventions are designed to align production capacity with operational goals, mitigate bottlenecks, and promote a stable, efficient, and sustainable crude palm oil production process.

Table 2 *Proposed new production line*

Station	Process
1	FFB received and place on ram
2	Sterilization
3	Threshing
4	Digester & Press
5	Deliver to oil room
6	Oil room

3.5 Step 8: Validation of Potential Solution for Improvement

Fig. 5 illustrates the proposed new crude palm oil production process, developed and analysed using Arena simulation software. The simulation highlights clear differences between the proposed process flow and the existing system. Notably, the production bottlenecks were significantly reduced in three key operations: FFB receiving and placing on the ram, and delivery to the oil room.

On the other hand, the data presented in Table 3 clearly show that some processes can be consolidated into a single entity by rearranging the process layout. In particular, steps 2, 3, and 4 can be combined. The same goes for steps 6 and 7. Furthermore, manual task-based activities such as tape and labelling need greater processing time. Changes can be made to decrease and eliminate waste, hence improving the efficiency and effectiveness of the furniture production process flow. This includes eliminating waste related to waiting and moving to improve overall production efficiency.

For the Delivering to Oil Room process, the total time per entity decreased from 8.15 units to 5.85 units. The wait time per entity was reduced from 5.84 units to 3.62 units, and the queue waiting time dropped from 6.85 units to 4.18 units. Similarly, the FFB Receiving and Place on Ram process showed improvement, with the total time per entity decreasing from 6.95 units to 4.38 units, and both the stage wait time and queue wait time reduced from 6.42 units to 3.84 units.

At the Sterilization station, which previously had an average cycle time of 79.77 minutes, the total time per entity was reduced to 1.81 units from 5.83 units. The wait time per entity decreased to 0.30 units (previously 4.34 units), and the queue wait time was also lowered to 0.30 units (previously 4.56 units). These improvements were achieved by increasing resource capacity through the addition of an extra sterilizer and implementing automated monitoring and control systems, which minimized manual adjustments, enhanced consistency, and shortened cycle times.

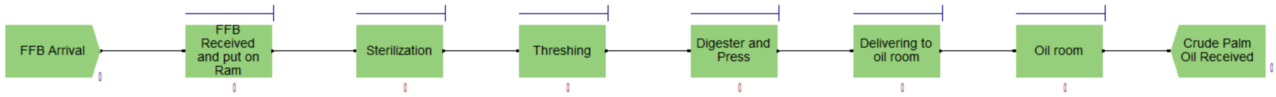

Fig. 5 *Improved layout of CPO production line using Arena simulation*

Table 3 *Result based on discrete-time stats in Arena simulation*

Station	Process	Number of workers	Number of machines	Total time per entity (unit)	Wait time per entity (unit)	Wait time in queue (unit)
1	FFB received and place on ram	1	-	4.38	3.84	3.84
2	Sterilization	-	1	1.81	0.30	0.30
3	Threshing	1	1	4.37	4.29	4.29
4	Digester and press	1	1	4.78	4.26	4.26
5	Delivering to oil room	1	1	5.85	3.62	4.18
6	Oil room	1	1	5.13	0.77	0.85

Table 4 *Comparison between current and improve resource capacity*

Current		Process	Improved	
No. of resource capacity	Station		Station	No. of resource capacity
1	1	FFB received and place on ram	1	2
1	2	Sterilization	2	2
1	3	Threshing	3	2
1	4	Digester	NA	NA
1	5	Press	NA	NA
NA	NA	Digester and Press	4	2
1	6	Deliver to oil room	5	2
1	7	Oil room	6	3

Overall, these enhancements demonstrate the effectiveness of the proposed solutions in eliminating bottlenecks, improving workflow efficiency, reducing processing times, and optimising resource utilisation. Consequently, the production line achieves more stable output and greater operational reliability.

4. Conclusion

As shown by the suggested solutions and analyses, any company that aspires to continuously enhance its production efficiency must employ all available ways to attain this aim. At each stage of the product life cycle, optimization alternatives are assessed to increase manufacturing efficiency and save both financial and human resources. This needs both software support and managerial strategies. The simulation modelling was carried out using the company's current data, and after several observations and discussions, improvements were suggested. According to the simulation findings, the recommended new process distribution for the shoe rack assembly line highlights the differences from the existing one. Surprisingly, manufacturing capacity increases considerably, from 358 to 1027 units. Thus, it is possible to determine that numerous alterations may be implemented to increase the overall efficiency of the present assembly line in comparison to other workstations. To ensure that the reform is thorough and successful, changes must be advocated at all levels of the company, from the top down. By implementing the potential solution to solve the identified bottleneck, the company may save both financial and human resources while also reducing the time required to produce the product in issue.

In conclusion, the implementation of Arena Simulation in the crude palm oil production process effectively identified and addressed key bottlenecks, resulting in significant productivity improvements. The study focused on three main bottlenecks: delivery to the oil room, sterilisation station, and FFB receiving and loading onto the ram, applying solutions such as increasing resource capacity, streamlining processes, and optimising process durations. For the delivery to the oil room, increasing resource capacity reduced the total time per entity from 8.15 units to 5.85 units, representing a 28.2% improvement. At the sterilisation station, optimising process durations through automation and better scheduling decreased cycle time from 5.83 units to 1.81 units, achieving a 69% improvement. The FFB receiving and loading onto the ram process showed a 37% improvement, with total time reduced from 6.95 units to 4.38 units by increasing resource capacity.

Overall, increasing resource capacity provided the most substantial improvement, particularly at the sterilisation station, highlighting the importance of addressing resource limitations to alleviate production delays and enhance workflow efficiency. Each solution, however, contributed uniquely to resolving specific bottlenecks, demonstrating the need for a tailored approach to process optimisation. Implementation challenges may arise, including the financial investment required for additional equipment and personnel, temporary disruptions from process reconfiguration and automation integration, and the need for upskilling employees while managing resistance to change. Addressing these challenges requires strategic planning, phased implementation, and effective stakeholder communication. By overcoming these barriers, the production process can achieve sustained productivity, reduced processing times, and more stable crude palm oil output. This study underscores the value of simulation-based methodologies as powerful tools for modern manufacturing operations seeking operational excellence and long-term competitiveness.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Tee Bing Hong Anthony, Mohamad Ali Selimin;* ***data collection:*** *Tee Bing Hong Anthony;* ***analysis and interpretation of results:*** *Tee Bing Hong Anthony, Mohamad Ali Selimin, Nor Aziati Abdul Hamid;* ***draft manuscript preparation:*** *Tee Bing Hong Anthony, Mohamad Ali Selimin. All authors reviewed the results and approved the final version of the manuscript.*

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