Development of Sensor Monitoring for Loss Reduction Analysis in Palm Oil Extraction Process

T. Chucheep[1], N. Mahathaninwong[1*], S. Limhengha[1] & N. Suvonvorn[2]

ARTICLE INFO

Article details
Submitted by authors 16 Oct 2024
Accepted for publication 18 Apr 2024
Available online 30 May 2025

Contact details
* Corresponding author
narissara.s@psu.ac.th

Author affiliations
1 Faculty of Science and Industrial Technology, Prince of Songkla University, Surat Thani Campus, Muang, Surat Thani, Thailand

2 Department of Computer Engineering, Intelligent Automation Research Center (IARC), Faculty of Engineering, Prince of Songkla University, Hat Yai, Songkhla, Thailand

ORCID® identifiers
T. Chucheep
https://orcid.org/0000-0001-9890-6422

N. Mahathaninwong
https://orcid.org/0000-0002-3785-9105

S. Limhengha
https://orcid.org/0000-0003-3242-2200

N. Suvonvorn
https://orcid.org/0000-0002-7057-227X

DOI
http://dx.doi.org//10.7166/36-1-3122

ABSTRACT

This study developed sensor monitoring equipment for palm oil extraction processes to track digester and press operations and their impact on fibre oil loss and nuts cracking in the press cake. Using a human monitoring and control system revealed delays, inaccuracies, and possible losses. Analysis of scenarios A-D, considering running capacity, fibre oil loss, and nuts cracking, indicated monthly losses ranging from US$32,058 to US$44,853. The sensor monitoring and human control system provided accurate feedback, reducing losses. The reduction scenarios of 10% and 20% suggested potential monthly reductions of US$3,206 to US$8,971.

OPSOMMING

Hierdie studie het sensormoniteringstoerusting vir palmolie-ekstraksieprosesse ontwikkel om verteer- en persbedrywighede en hul impak op veselolieverlies en neute wat in die perskoek kraak, na te spoor. Die gebruik van 'n menslike monitering- en beheerstelsel het vertragings, onakkuraathede en moontlike verliese aan die lig gebring. Ontleding van scenario's A-D, met inagneming van loopvermoë, veselolieverlies en neute wat kraak, het maandelikse verliese aangedui wat wissel van US$32,058 tot US$44,853. Die sensormonitering en menslike beheerstelsel het akkurate terugvoer verskaf, wat verliese verminder het. Die verminderingscenario's van 10% en 20% het moontlike maandelikse verlagings van US$3,206 tot US$8,971 voorgestel.

1. INTRODUCTION

Thailand holds the third position in palm oil production, contributing only 3.8% of the global output, which has a minimal influence on world market prices. The majority of Thai oil palm plantations and mills (85%) are located in the southern provinces, particularly in Krabi, Surat Thani, and Chumphon [1]. The country currently operates 70 crude palm oil mills (POMs) with a combined production capacity of about five million tons per year [1].

The POMs are characterised by their high production capacity, which is primarily driven by the screw press machine that extracts both the liquid phase (crude palm oil and water) and the solid phase (mesocarp fibre, nuts, broken kernel, and shell) [2]. The oil yield obtained from the pressing process significantly influences industrial competitiveness. However, improper control of pressing process parameters can lead to fibre oil loss. The preparation of mesocarp through a digestion process also plays a crucial role in fibre oil loss. Baryeh [3] conducted a study of extraction pressure, heating time, and heating temperature using a hand press, and revealed their effects on oil yield. The selection of appropriate processing parameters and diligent monitoring of the entire process, as suggested by Adetola *et al.* [4], are significant factors to be considered in the POMs. In addition, the study identifies limitations related to palm type, specifically the Tenera species [5].

To enhance oil yield efficiency, POMs are increasingly adopting sensor technology to monitor parameters. The cost effectiveness of sensors, the Internet of Things (IoT), and Industry 4.0 has led to their widespread application in monitoring machine automation and maintenance, enabling cost-benefit analyses with different types of maintenance (corrective, time-based, and condition-based) [6]. However, effective integration between humans and machines is essential when using sensors. Grandjean [7] describes the man-machine system interface, and emphasises the role of operators in decision-making that is based on perception data. Breton and Bossé [8] discuss the potential of automation systems in addressing problems in environments with numerous sources of information, which can lead to fatigue and human errors. Klumpp *et al.* [9] highlight the interdisciplinary nature of cyber-physical systems (CPS), including Industry 4.0 and IoT, and their impact on human-computer interaction (HCI) and efficient collaboration.

In the POMs, the combination of sensor monitoring and human control (SM&HC) enables operators to make informed decisions based on real-time data. Operators read and analyse parameter processes from displays to control the machine effectively. Maintaining the appropriate combination of processing parameters is essential for oil yield and to minimise fibre oil loss, particularly when using the human monitoring and controlling (HM&C) system. Transparency in the sensor-generated data facilitates planning, scheduling, and controlling [10]. The application of SM&HC differs from full automation, as it combines the expertise of operators with real-time data from sensors, which facilitates informed decision-making. This paper focuses on analysing the benefits of reducing SM&HC loss in a POM.

2. METHODOLOGY

The analysis focused on the benefits of implementing a portable SM&HC system in a POM located in southern Thailand. The POM had four sets of digester and screw press machines, each with a maximum capacity of 25 tons per hour, equipped with a total of 16 sensors (four sensors per machine set) to monitor processing parameters. Evaluation of HM&C loss occurred through scenarios involving running capacity, fibre oil loss, and nut crack loss, using three-month operation data during May and June 2023. A benefit analysis was conducted by considering the reduction in the HM&C loss achieved through portable SM&HC.

2.1. Human monitoring of digestion and pressing and process control

The digestion and pressing process involved the preparation of mesocarp through digestion and subsequent oil extraction using a screw press machine (Figure 1). The digestion process used a tank with steam injection and a propeller to separate the nuts from the mesocarp. Three sets of rotary stirrers in the digester ruptured oil cells in the palm fruit.

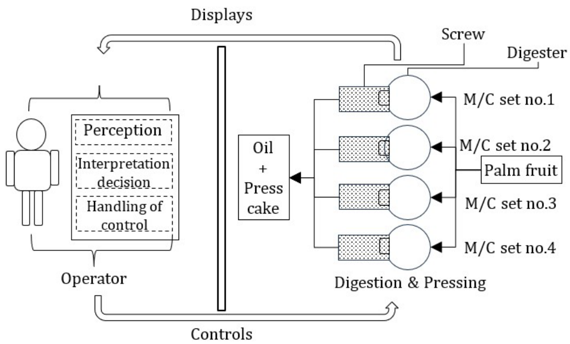

Figure 1: Diagram of digestion and pressing HM&C

In the HM&C system, check sheets were used by the operators to monitor parameters such as digester temperature and it stirrer current as well as screw press pressure and it current via different displays. In this control cycle, data were recorded on a check sheet every two hours, and the operators were responsible for adjusting machines during the production process (Figure 1). The HM&C system followed a 'human-physical system' model in which the physical system acted as the 'executing body' for tasks while humans oversaw and used these systems. Within this framework, humans engage in activities such as perception, cognition, learning, analysing, operating, and decision-making [11].

Scenario analysis was used to analyse multiple factors, each with various levels. For instance, Chucheep *et al.* [12] used the scenario analysis to assess the benefits of reducing band saw wear under different changeover rates, machine numbers, and sawing rates. Meanwhile, Lie *et al.* [13] used such analysis for continuously monitoring system failures. The parameters in operating the digester and press machine affected the quantity of fibre oil loss and nut cracks in the press cake. The quantity of fibre oil loss varied inversely with the quantity of cracked nuts. Therefore, scenarios of high level fibre oil loss were analysed in conjunction with low-level nut crack loss; conversely, scenarios of low-level fibre oil loss were analysed with high-level nut crack loss. The variables for analysing losses included running capacity, fibre oil loss, and nut cracking. These loss scenarios combined three factors: running capacity (low level [18,000] and high level [23,760]); fibre oil loss (low level [5.02%] and high level [5.42%]); and nut crack loss (low level [12.75%] and high level [13.88%]). These were labelled A (L,H,L), B (L,L,H), C(H,H,L), and D (L,H,L) respectively, and are shown in Figure 2. The HM&C loss was calculated by multiplying the volume of fibre oil loss in each scenario by an approximate value of semi-crude oil at US$0.54 per kg (THB20 per kg) at an exchange rate of THB36.8165 per US dollar [14] (Figure 2).

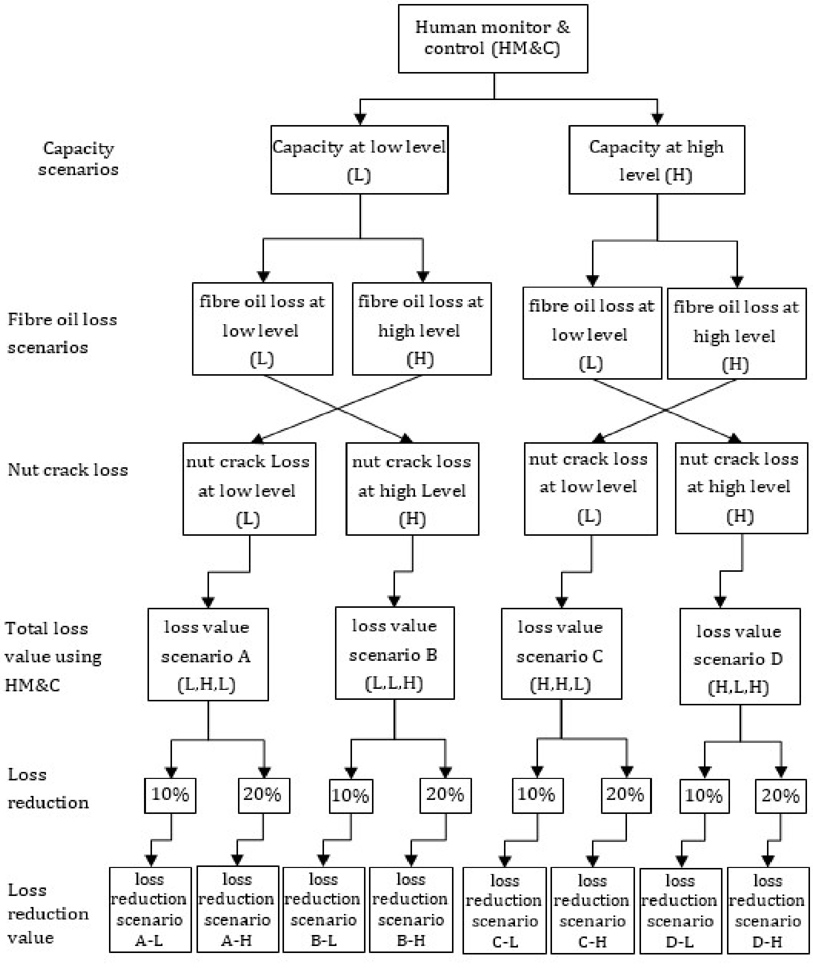

Figure 2: Scenarios of loss when using HM&C and loss reduction when using SM&HC

The calculation of the total value of the loss in press cake was determined by the quantity of fibre oil loss that exceeded 4%. The total loss value in the press cake was calculated on the basis of the excess amount beyond the threshold values for fibre oil loss and nut cracks. The threshold values for fibre oil loss and nut cracks were 4% and 10% respectively, which served as criteria for the oil palm milling process, as formulated in Equation (1). Oil loss in the mesocarp was about 5% to 6%, as indicated by Corley and Tinker [15], Purnama *et al.* [16], Wenten *et al.* [17], and Obibuzor *et al.* [18]. The factory's fibre oil loss criterion, set at 4%, was lower than the one established by Hermantoro *et al.* [19], which was set at 5%. Similarly, the factory's nut crack criterion of 10% was equal to that established by Hermantoro *et al.* [19].

Total HM&C loss = Value of fibre oil loss over 4% + Value of nuts crack loss over 10% (1)

The estimated value of fibre oil loss (Equation 1) was about 90% of the crude palm oil (CPO) value, based on the main processes outlined in the material flow chart: screening, settling tank, centrifuge, and vacuum dryer, according to the Palm Oil Research Institute [5], or clarification, purifying/drying, and storage according to Chew *et al*. [20]. The formulation was Equation (2), where P_C is a drying kernel price and F_L is a fibre oil loss scenario:

$$\text{Value of fibre oil loss} = (0.9) \times (P_C) \times (F_L - \text{operating loss criterion } (4\%)) \quad (2)$$

The calculation of the value of the nut crack loss (Equation 1) was estimated, as formulated in Equation (3), at 80% of the dry kernel value, considering the several main processes outlined in the material flow chart of the Palm Oil Research Institute [5]. The selling price of kernels was set at US$0.38 per kg. In Equation (3), P_K is a drying kernel price and N_{CL} is a nut crack loss scenario:

$$\text{Value of nut crack loss} = (0.8) \times P_K \times (N_{CL} - \text{operating nut crack criterion } (10\%)) \quad (3)$$

2.2. Design of digestion and pressing SM&HC

Two sensors – a thermocouple (PT100, Model TSP-08) for measuring palm fruit temperature (di-temperature) and power sensors (di-current) for the stirrer motor current – were designed to monitor the digestion process. In addition, other two sensors – power sensors (KTC-36 500A/5A) to track the motor current in a screw press machine and pressure sensors (8287.34.2517 Pressure Sensor 0-250bar 4-20mA Trafag) to oversee its hydraulic pressure – were used for the screw press machine. The SM&HC system was used in commercial sensors for proximity, type K temperature, current (0-100 A) with output (0-24 mA), together with pressure sensors (0-100 kg per cm^2). The system also used a sensor receiving data unit, long-range data communication with a maximum distance of 3,000 meters [21], a display-recording and control unit (as shown in Figure 3), along with portable displays for the operator's control room and the supervisor's office. The system facilitated data collection and transfer through long-range (LoRa) data communication via serial RS 485 to the portable recording and control unit for real-time monitoring and decision-making.

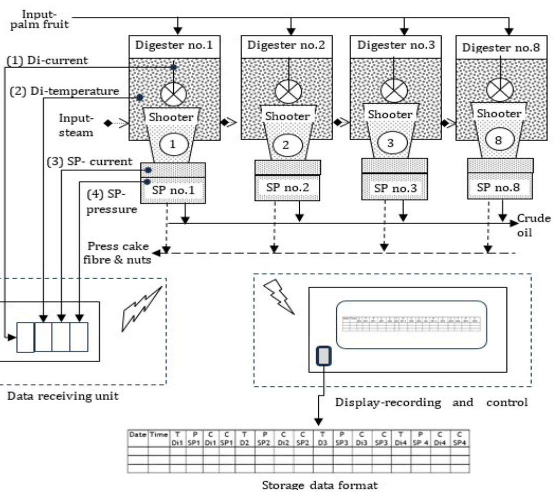

Figure 3: Design of digestion and pressing SM&HC

2.3. Installing monitoring system for sensors

The sensor monitoring system comprises three main parts (Figure 4): (1) installation of four sensors for each set of digestion and pressing machines; (2) a sensors' data receiving unit; and (3) a portable display-record and control unit for the operator and supervisor's office. The design uses plug-and-play sensors and commercial long-range data communication technology to reduce wiring costs and to enhance operational efficiency. However, installing sensors on digester and pressing machines requires shutting down machine operations and the involvement of highly skilled technicians with expertise in electrical systems, which became an operational limitation in fitting the equipment.

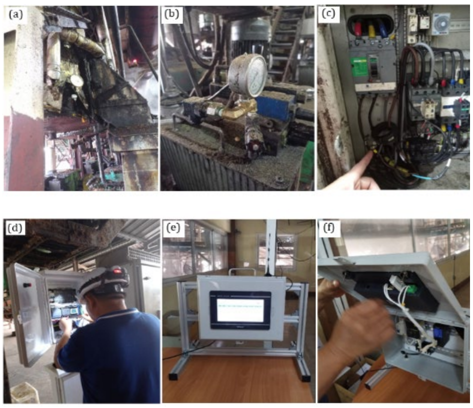

Figure 4: SM&HC (a) digester temperature, (b) pressure sensor, (c) current sensor, (d) sensor receiving data unit, (e) portable display-record and control unit, and (f) retrieving data

2.4. Benefit of reduced HM&C losses by installing SM&HC system

The reduced losses in the HM&C system came from using the man-machine system's working mechanism in which operators received parameter data from every digester and pressing machine via a portable display in real time. This was faster than the traditional HM&C parameter inspection process (Figure 5). The design of the SM&HC system was compared with a digital manufacturing system, which is characterised by the emergence of a cyber system between the human and physical systems. Supervisors monitored the machine operation parameters in real time to control and command parameter adjustments as needed (Figure 5). Furthermore, the ability to trace the machine operation's parameters allowed for retrospective analysis to identify areas for improvement.

The benefit of reducing HM&C loss stemmed from obtaining rapid and precise data and easing decision-making. Cost-reduction scenarios were established on the basis of primary figures from a condition-based maintenance strategy for offshore wind turbines. These scenarios aimed to decrease operational lifetime costs by 20% compared with preventive maintenance, which was simulated using hidden Markov models by May and McMillan [22]. The scenarios ranged from 10% (low level) to 20% (high level); see Equation (4).

Benefit = {Value of HM&C total loss scenario A-D} x {Reduction level (10%, 20%)} (4)

The analysis scenarios to reduce human monitoring and control loss encompassed the entire benefit analysis of eight scenarios, including the benefits of a 10% reduction in four scenarios (A-L, B-L, C-L, and D-L) and a 20% reduction in scenarios A-H, B-H, C-H, and D-H. The details of all the benefit scenarios are shown in Figure 2 above.

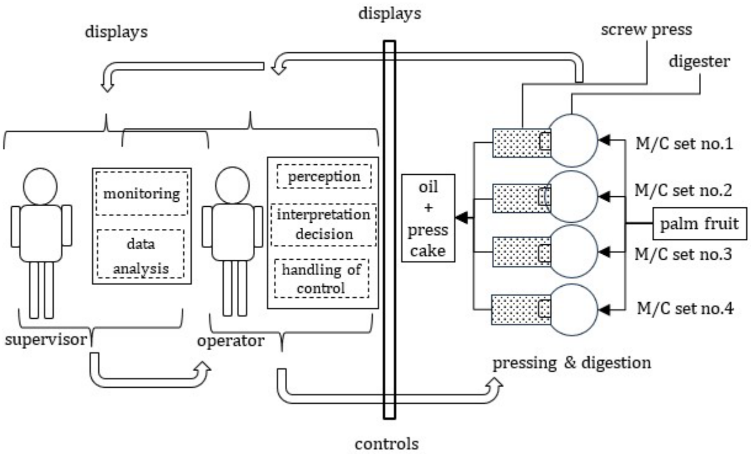

Figure 5: Diagram of portable SM&HC

3. RESULT

3.1. Losses in the HM&C system

Using check sheets, shift reports, and daily reports with lower accuracy leads to slower adjustments to the digester and pressing machine. Low-speed control results in exceeding the criteria for both fibre oil and nut crack losses. The total values of the losses were the one for fibre oil loss of over 4% (Equation 2) and the one for nut crack loss of over 10% (Equation 3) in the press cake.

3.1.1. Losses in the HM&C scenarios

The variables in analysing the HM&C losses consisted of running capacity, fibre oil loss, and nut crack loss. The details of setting the levels for each factor were derived from the operational data for May, June, and July 2023. The capacity variable, which came from the production quantity data over the same three months, summarised the monthly machine operations for machine sets no. 1-4 (Table 1). The production quantities of fresh fruit bunches (FFB) were 22,080 tons in May, 18,000 tons in June, and 23,760 tons in July, as shown in Table 1. The low production capacity range was then set at 18,000 tons and the high level at 23,760 tons of FFB per month. The variable in the amount of fibre oil loss was derived from the laboratory analysis of the fibre oil loss from press cake during the three-month production period, which provided the summarised information presented in Table 2, which displays the results of the analysis of cracked nuts corresponding to the quantity of oil loss in fibres.

Table 1: Capacity scenarios

Month	Running of digester & screw press M/C no.1		Running of digester & screw press M/C no.2		Running of digester & screw press M/C no.3		Running of digester & screw press M/C no.4		Production quantities (tons FFB per month)
	Shift A	Shift B	Shift A	Shift B	Shift A	Shift B	Shift A	Shift B	
May 2023	14.00	13.00	14.00	14.00	15.00	15.00	4.00	3.00	22,080
June 2023	12.00	13.00	12.00	13.00	12.00	13.00	0.00	0.00	18,000 (L)
July 2023	16.00	15.00	14.00	13.00	12.00	10.00	8.00	11.00	23,760 (H)

Table 2: Fibre oil loss scenarios

Month	Fibre oil loss (%)		Detail of running M/C	Screw press motor current (Ampere)	Nuts crack (%)
May 2023	Mean	4.53	N/A	N/A	N/A
May 23, 2023	Min.	3.55	M/C set no.3; Shift A	63.15	10.73
May 23, 2023	Max.	5.42 (H)	M/C set no.2; Shift A	58.40	8.45
June 2023	Mean	4.25	N/A	N/A	N/A
June 13, 2023	Min.	3.22	M/C set no.2; Shift A	58.80	7.63
June 13, 2023	Max.	5.04	M/C set no.2; Shift B	56.20	7.98
July, 2023	Mean	4.46	N/A	N/A	N/A
July 29, 2023	Min.	4.04	M/C set no.1; Shift A	61.15	7.57
July 11,2023	Max.	5.02 (L)	M/C set no.2; Shift A	69.50	10.34

Table 2 also shows the maximum fibre oil loss for each month: 5.42% in May, 5.04% in June, and 5.02% in July. The 5.42% in May was set as the high level of fibre oil loss, while the 5.02% in June was set as the low level. The fibre oil loss in the case study exceeded the factory standard of 4%. However, compared with the criteria set by Hermantoro *et al.* [19], which specified a fibre oil loss threshold of not more than 5.0%, it was only slightly higher. Table 3 shows the maximum nuts crack loss in May (13.26%), June (13.88%) and July (12.75%) which exceeds the factory's operational standard by 10% and aligns with the criterion established by Hermantoro *et al.* [19]. Therefore, the low-high scenarios range of nuts crack loss for analysis is set between 12.75 and 13.88%. In Table 3, the nuts crack percentage in July is low at 12.75% and the fibre oil loss is also low at 3.99%. This data implies that other factors may affect oil loss and nuts cracks.

Table 3: Nut crack loss scenarios

Month	Nuts crack (%)		Detail of running M/C	Screw press motor current (amperes)	Fibre oil loss (%)
May 2023	Mean	9.13	N/A	N/A	N/A
May 11, 2023	Min.	3.75	M/C set no.1; Shift B	64.40	4.19
May 22, 2023	Max.	13.26	M/C set no.2; Shift B	63.90	4.70
June 2023	Mean	9.07	N/A	N/A	N/A
June 4, 2023	Min.	5.43	M/C set no.1; Shift B	64.40	4.28
June 24, 2023	Max.	13.88(H)	M/C set no.1; Shift B	65.30	4.16
July 2023	Mean	8.68	N/A	N/A	N/A
July 12, 2023	Min.	4.51	M/C set no.3; Shift B	68.60	4.58
July 19, 2023	Max.	12.75(L)	M/C set no.4; Shift A	66.45	3.99

3.2. Total loss from human control and monitoring

The calculation of the total loss value from HM&C is based on the data range scenarios from Figure 2, the running capacity (18,000, 23,760) from Table 1, the fibre oil loss quantity (5.02, 5.42) from Table 2, and the nut crack quantity (12.75, 13.88) from Table 3. The value of the fibre oil loss was calculated using Equation (2), with the fibre oil loss value set at 90% of the selling price of crude palm oil, the fibre proportion per FFB set at 13%, and the maximum threshold for oil loss in fibres during machine operation set at 4%, as specified in section 2.1.

Value of HM&C fibre oil loss scenario A = (0.9)(0.54)x(18,000x1,000x0.13)x(0.0542-0.04)

= US$16,245 per month

Equation (3) was used to calculate the value of nut crack loss, with the estimated value of nuts crack set at 80% of the price of dry kernels, as detailed in section 2.1. The proportion of press cake (fibre and nuts) was set at 25% of the FFB, with the proportion of nuts in the press cake being 42%.

Value of nut crack loss scenario A = (0.8)(0.38)x(18,000x1,000x0.25)(0.42)x(0.1275-0.10)

= US$15,813 per month

Total loss scenario A = US$16,245 + US$15,813 = US$32,058 per month

Scenarios B and D revealed low-level quantities of fibre oil loss, with the oil loss in fibres amounting to 1.02% (5.02%-4.00%), whereas scenarios A and C showed high-level quantities of fibre oil loss at 1.42% (5.42%-4.00%). For scenarios A and C, the nut crack quantities were at a low level of 2.75% (12.75%-2.75%), while its quanties in scenarios B and D were at a high level of 3.88% (13.88%-10.00%).

Figure 6 shows that the factory criterion for the total loss of excess ranged from US$32,058 (scenario A) to US$44,853 (scenario D) per month. The maximum value of fibre oil loss occurred in scenario C, with a capacity of 23,760 tons per month and a fibre oil loss of 5.42%, resulting in a loss value of US$21,443 per month, accounting for 51% of the total loss. Meanwhile, the highest value of nut crack loss was observed in scenario D, with a production capacity of 23,760 tons FFB per month and a cracked nuts quantity of 13.88%, resulting in a loss value of US$29,450 per month, constituting 65.7% of the total loss value. That 65.7% highlighted the importance of controlling nut cracking during fibre oil loss control. The technology of kernel-free pressing would be suitable for minimising fibre oil loss and nut cracking, as suggested by Wondi *et al.* [23].

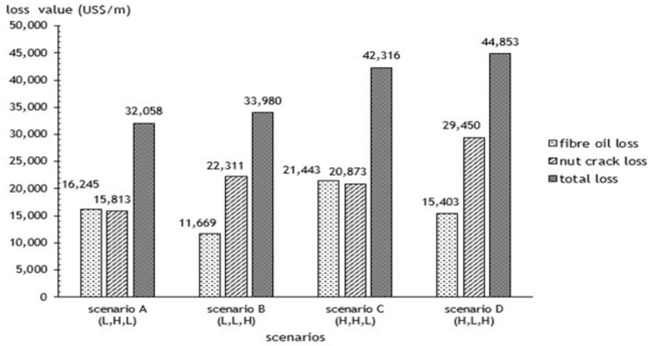

Figure 6: Total loss value in HM&C scenarios

3.3. Reduction of loss value using portable SM&HC

The use of SM&HC by installing sensors in the digestion and pressing processes showed real-time results while ensuring accuracy and precision. This real-time feedback enabled retrospective analysis, facilitating rapid and convenient process control. It established a supervisory control mechanism, allowing for the analysis of overall loss reduction. Matyas *et al.* [24] introduced a prescriptive maintenance approach for triaxial machining centres in the automotive industry by aiming to reduce overall maintenance costs of 30% (avoidance of direct and indirect failure correction costs) and to increase maintenance planning savings by 20%. The system architecture included data acquisition, preprocessing, analysis, simulation, failure prediction, and a prescriptive maintenance decision support model. It optimally predicts future malfunctions, and recommends the maintenance actions that technicians should take. The analysis of process data to bring about improvements involves the presentation of real-time data that include the date, time, and process parameters of the digester temperature, the screw press pressure, the digester current, and the screw press current for machines numbered 1 to 4. To achieve a balanced manufacturing system that maximises profit without compromising product quality, it would be essential for operators and machines to interact properly. This balance could be attained by categorising activities into information handling and physical work so that the subsequent tasks in each category could be allocated according to the ‘level of automation’ [25].

3.3.1. Basic analysis of data from portable sensor monitoring

The portable sensor monitoring of the SM&HC system features a portable monitoring display that receives data wirelessly from the sensors. This portability allows the operators to monitor real-time data and to take prompt control actions from their office or from other designated locations. In contrast, a fixed display is integrated into the HM&C system, in which data are recorded every two hours using a check sheet. The data obtained from the SM&HC system have proven invaluable in providing precise and transparent information with the capacity to be traced. The system delivers detailed data at intervals of every five minutes, as shown from 08:00 to 19:55 on 9 January 2024 for machine sets nos.1–4 (Figure 7). The international standard for integrating enterprise and control systems (ISA 95) has five categories or levels. Level 1 contains intelligent devices responsible for measuring and manipulating the physical processes on site, and common instruments at this level are sensors, analysers, effectors, and related equipment; and level 2 represents the control and supervision of the underlying activities [26]. The SM&HC system meets the criteria of level 1.

As mentioned earlier, the data fluctuate constantly. The data from machine sets nos. 1-4 (Figure 7) show that set no. 2 stopped at 10:05, as indicated by the screw press hydraulic pressure (SP pressure 2 in Figure 7(b)), the motor digester current (di-current 2 in Figure 7(c)), and the motor screw press current (SP current 2 in Figure 7(d)), while the digester’s temperature gradually decreased (di-temp 2 in Figure 7(a)). Furthermore, examining the parameters in operation between 08:00 and 10:00, the hydraulic pressure of screw press no. 2 was higher than the others (Figure 7(b)) before the shutdown. At the same time, the digester current no. 1 showed a higher average value than the other machines, peaking at 89.7 amperes at 14:00 and dropping to 38.2 amperes at 19:20 (Figure 7(c)). The palm fruit feeding pattern from the threshing machine to digesters no. 1, 2, 3, and 4 affected digester no. 1, which is always full during production. A further assessment of the palm fruit levels in the digester would be needed. Moreover, the kernel press current correlated with the wear of the stirrer blade in the digester and of the worm screw in the press screw.

The efficiency of the screw press plays a crucial role in maximising oil extraction, as a poorly functioning press can lead to increased oil loss and maintenance expenses. Maintaining stable press cage pressure in the screw press system is pivotal in minimising oil loss and nut breakage in the press cake. While a higher pressure enhances oil recovery, it also raises the risk of nuts cracking [27]. For instance, if the digestion process involved a blend of oil palm fruit with a high Pisifera to Tenera/Dura ratio, there would be notable oil retention in the pressed mesocarp fibre and sludge. This could be attributed to the Pisifera's elevated mesocarp-to-kernel ratio, which would create problems for the press and yield substantial sludge, causing inefficient oil retrieval. In addition, inefficient shearing by the digester's stirrer could contribute by failing fully to rupture the oil-bearing cell walls to release the oil [28]. The quantities of fibre oil loss and nut crack occurring during the stirring and pressing processes result from the various causes mentioned above. SM&HC offers advantages, as humans have strengths such as sensing unexpected stimuli, devising new solutions to problems, generalising from observations, and making decisions based on incomplete data [29]. Concerning the oil extraction rate (OER), Chew *et al.* [20] note that it depends on various factors, such as the oil content in oil palm fruit, the maturity of the oil palm trees, soil conditions, the climate, harvesting techniques, fruit quality, and the efficiency of the oil extraction processes in the mills. In addition, their study estimated that the milling efficiency of a well-managed mill in Malaysia was around 90%, which resulted in an oil loss equivalent to 1.5%–2.0% of the OER. In Thailand, the Ministry of Industry's 2019 notification [30] mandated that POMs had to achieve an OER of no less than 18%.

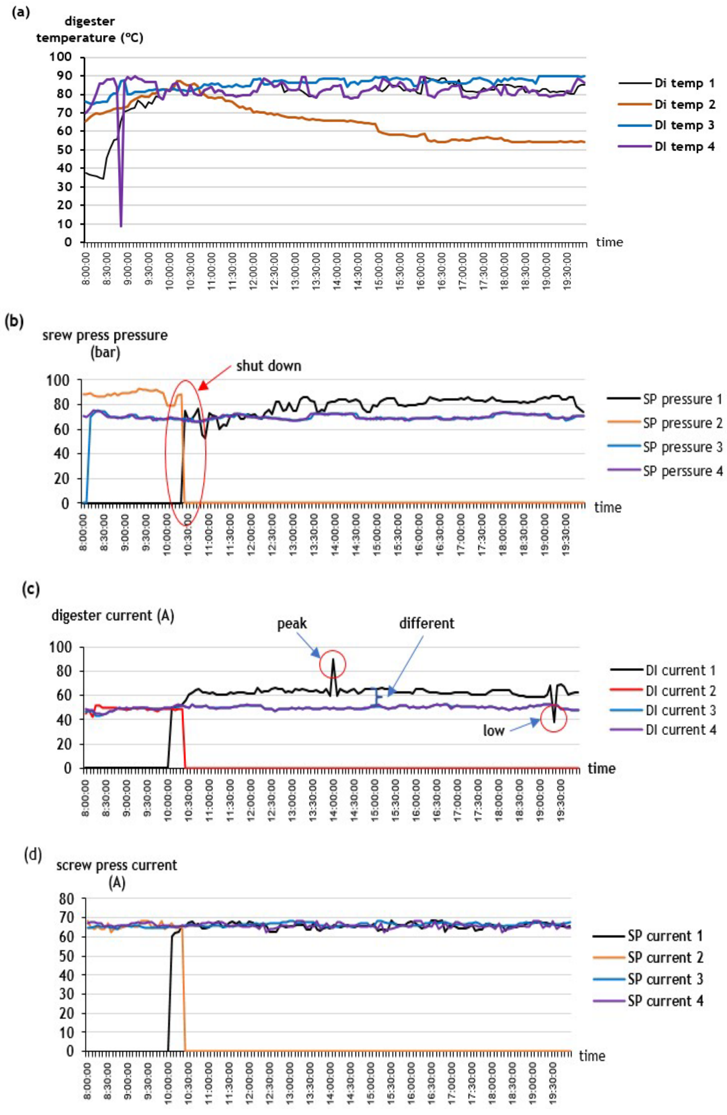

Figure 7: Retrieved data from SM&HC: (a) digester temperature; (b) screw press pressure; (c) digester current; and (d) screw press current

3.3.2. *Reduction of loss value using portable SM&HC*

The analysis of the scenario-based reductions in total loss (A-L, B-L, C-L, and D-L) revealed that the use of an SM&HC system that displays real-time and accurate process parameter data could lead to reduced loss. In the low-level scenario, the total loss values for scenarios A (US$3,206), B (US$3,398), C (US$4,232), and D (US$4,485) per month were reduced (Figure 8(a)). The reduced loss, thanks to SM&HC, stemmed from the availability of real-time data and the ability to cross-check and analyse retrospective data, which was a significant improvement over traditional HM&C. When considering the possibility of further reducing the loss value by 20% (Figure 8(b)), the highest level of reduction in scenario D-H amounted to US$8,971 per month. For the SM&HC system to function at its best, training in using data from the portable display-record and control unit would be essential, as it would ensure swift process control and data analysis, yielding retrospective insights. The losses in press cake were influenced by various parameters such as FFB ripeness, the sterilisation process, the digester blade life, and the worm screw life. Given the high running capacity of the POMs, even small decreases in quantity could lead to significant reductions in value. In this study, with a capacity of 18,000 to 23,760 tons per month, a 20% reduction in losses would result in a significant reduction of up to US$8,971 per month.

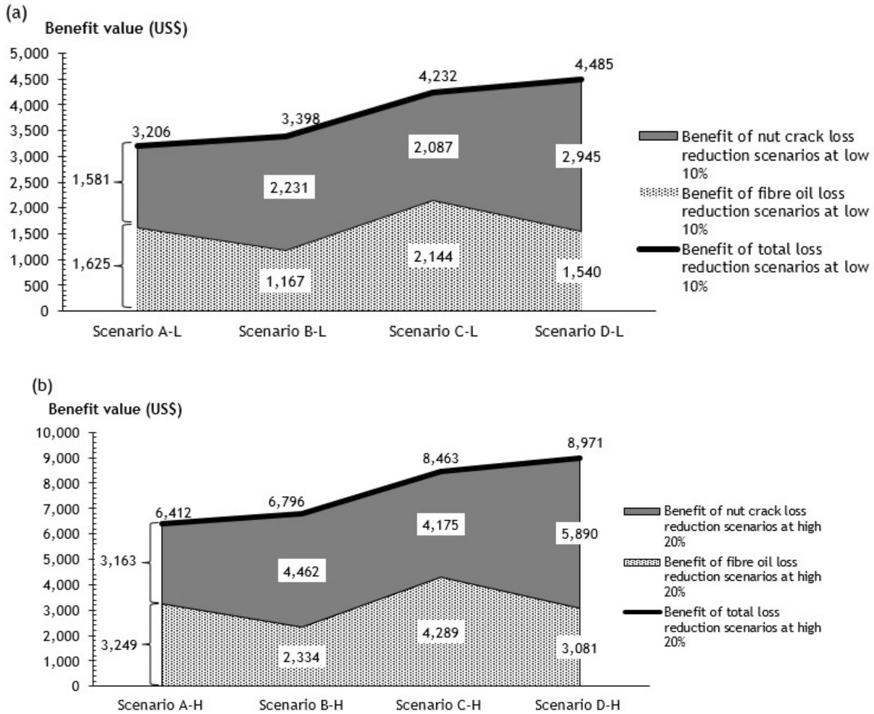

Figure 8: Loss reduction scenarios of implementing SM&HC (a) at 10% level and (b) at 20% level

4. DISCUSSION

Typically, the digester temperature, screw press pressure, digester current, and screw press current of the palm oil milling process are monitored using check sheets, shift reports, and daily reports – that is, the HM&C system. However, imprecision and inaccuracy in using the HM&C system is possible. For instance, the check sheets recording the parameter values for every two hours on 9 January 2024 were submitted at the end of the workday, and showed inconsistencies in some parameters. Examples were the digester temperature for machine No. 1 at 80° C, the hydraulic pressure for screw press No. 2 at 70 bar, and the motor current for screw press No. 2 at 65–67 amperes. However, these methods have limited accuracy, leading to slower adjustments to the digester and the pressing machine. In actual production, it is unlikely that parameter values remain constant throughout the operational period. Insufficient process control may lead to significant losses in fibre oil and to nut cracking, as observed in the study of Kandiah *et al.* [31], which reported on the daily performance of the Bukit Puteri Mill's press machine no. 2, where the fibre oil loss ranged from 4.45% to 7.33% and broken nuts from 10.90% to 40.50%. The appropriate values for each machine set in the context of POM can vary; for example, the minimum fibre oil loss was 7.63% when the pressing machine was set at 80 bars [19], a heating time of 20 minutes, and an extraction time of 10 minutes at 80° C. This showed an extraction pressure of 25 MN per m^2, which, although relatively high, had a significant impact [3]. However, when the extraction pressure was lower than 25 MN per m^2, the oil yield decreased from 37% to 22%. In addition, higher temperatures generally result in higher yields than with those below 100° C. The system enhances transparency, enabling more effective planning, scheduling, and controlling of manual assembly processes, and leading to cost and time savings as well as to improved quality [10].

The oil yield from the pressing process is significantly influenced by factors such as the digester temperature, the screw press pressure, the digester current, and the screw press current in the palm oil milling process. Increased hydraulic pressure results in a greater number of cracked nuts [32]. Total losses from fibre oil loss and nut cracking are affected by various factors: (1) the FFB characteristics, such as palm tree age, varieties, harvesting practices, and fruit ripeness; (2) variation in the sterilisation process, such as the steam pressure and sterilisation time; and (3) variations in the digestion and pressing process, including machine wear and parameter control. In addition, fluctuations in the digester current (No. 1 parameter), as shown in Figure 7(c), cannot be effectively detected using traditional HM&C methods such as check sheets, thus highlighting the limitations of human-based monitoring. Integrating sensors for data collection while retaining human decision-making would be a suitable approach for traditional POMs that lack automation. The SM&HC system offers a real-time and comprehensive view of the process, enabling operators to make better decisions and more precise adjustments. Sensor data serve as a reliable source of information, fostering continuous improvement in the palm oil production process.

The portable sensor monitoring system in the SM&HC framework is designed for ease of use, and it can be deployed wherever it is needed in the oil palm milling plant. It can be seamlessly integrated with existing production processes and machinery without requiring modifications, thus addressing a key concern among mill owners. In addition, some sensors from the HM&C system are compatible with the SM&HC system, ensuring smooth implementation and enhanced monitoring capabilities. The losses associated with the HM&C system, particularly fibre oil and nut crack losses, are significant in mills processing 18,000 to 23,760 tons of FFB per month, with total losses ranging from US$32,058 to US$44,853 per month (based on scenarios A to D). Implementing the SM&HC system would enable rapid, precise, and comprehensive data feedback, which is particularly valuable when operators manage multiple functions. The impact of automation on human operators varies: automating the gathering of information only increases the mental workload, fatigue, and error rates, whereas automating both information-gathering and situational understanding would reduce these problems and improve process efficiency. Sensor-based monitoring provides ongoing insights into the process parameters, ensuring stable, accurate, and traceable control. The transparency of sensor-obtained data is crucial for effective process control planning, as shown in the research of Kärcher *et al.* [10]. The portable SM&HC system significantly improves the accuracy of feedback, reducing production losses. A 10% to 20% reduction in losses through this system could yield monthly savings of US$3,206 to US$8,971.

Moreover, the total losses from fibre oil loss and nut cracking depend on seasonal variations in the quantity of palm fruit bunches and on the machinery and the technological capabilities of each POM. Scenario analysis provides a structured approach to evaluating different conditions in various POMs.

5. CONCLUSION

This study has analysed the scenarios for total loss values that result from fibre oil loss and kernel cracking in the digestion and pressing processes. Each traditional palm oil extraction plant adjusted its digester and pressing machine parameters to suit various factors such as palm variety and the sterilisation process by using the HM&C system to track its machine operations. Key parameters that were tracked included digested temperatures of 95–100° C, stirrer motor currents of 65–70 A for the stirrer and screw press machine, and hydraulic pressures of 65–70 bars for the screw press machine. Analysing the scenarios with the HM&C system involved recording parameter values in check sheets, shift reports, and daily summaries. The variables included running capacity (18,000 and 23,760 tons per month), fibre oil loss (5.02% and 5.42%) and nut cracking (13.26%–13.88%), resulting in total loss values ranging from US$32,058 to US$44,853 per month. In addition, in scenario D, nut crack loss accounted for 65.7% of the total loss value. Analysing the reduction of fibre oil loss and nut cracking using the SM&HC system with two sensors for the temperature and motor current of the digester machines and with two sensors for the hydraulic pressure and motor current for the pressing machines generated real-time, transparent, and traceable data. The scenarios that reduced losses by 10% and 20% showed a potential monthly cost saving ranging from US$3,206 to US$8,971.

ACKNOWLEDGEMENTS

This research was financially supported by the National Science, Research, and Innovation Fund (NSRF) and Prince of Songkla University (Grant No. SIT6601230S), and Prince of Songkla University Surat Thani Campus, 2022. The authors thank Larp Pakdee Palm Company Limited Palm Oil Mill, located in Plaipraya District, Krabi Province, Thailand, for providing the case study.

REFERENCES

[1] **Chuasuwan, C.** 2018. Palm oil industry: Thailand industry outlook 2018-2020. *Krungsri Research*, April 2018. [Online] Available at https://www.krungsri.com/bank/getmedia/70f0c5ae-fa59-4117-812e-78a8cbcd24cc/IO_Oil_Palm_2018_EN.aspx [Accessed August 9, 2024].

[2] **Harun, M.Y., Che Yunus, M.A., Morad, N.A., & Ismail, M.H.S.** 2015. An industry survey of the screw press system in palm oil mills: Operational data and malfunction issues. *Engineering Failure Analysis*, 54, pp 146–149.

[3] **Baryeh, E.A.** 2001. Effect of palm oil processing parameters on yield. *Journal of Food Engineering*, 48, pp 1–6.

[4] **Adetola, O.A., Olajide, J.O., & Olalusi, A.P.** 2014. Effect of processing condition on yield of screw press expressed palm oil. *Journal of Emerging Trends in Engineering and Applied Sciences (JETEAS)*, 5(4), pp 243–247.

[5] **Palm Oil Research Institute.** 1994. *Palm oil factory process handbook. Part 1: General description of the palm oil milling process*. Shah Alam, Malaysia: Malindo Printers.

[6] **Verma, N. & Subramanian, T.S.S.** 2012. Cost benefit analysis of intelligent condition based maintenance of rotating machinery. *7th IEEE Conference on Industrial Electronics and Applications (ICIEA)*, pp 1930–1934.

[7] **Grandjean, E.** 1988. *Fitting the task to the man: A text book of occupational ergonomics*, 4th ed. London: Taylor & Francis.

[8] **Breton, R. & Bossé, É.** 2002. The cognitive costs and benefits of automation. *The RTO HFM Symposium on the Role of Human in Intelligent and Automated Systems*. Warsaw, Poland, 7–9 Oct 2002. Published in RTO–MP–088.

[9] **Klumpp, M., Hesenius, M., Meyer, O., Ruiner, C., & Gruhn, V.** 2019. Production logistics and human-computer interaction: State-of-the-art, challenges and requirements for the future. *The International Journal of Advanced Manufacturing Technology*, 105, pp 3691–3709.

[10] **Kärcher, S., Cuk, E., Denner, T., Görzig, D., Günther, L.C., Hansmersmann, A., Riexinger, G., & Bauernhansl, T.** 2018. Sensor-driven analysis of manual assembly systems. *51st CCIRP Conference on Manufacturing Systems. Procedia CIRP*, 72, pp 1142–1147.

[11] **Zhou, J., Zhou, Y., Wang, B., & Zang, J.** 2019. Human-cyber-physical systems (HCPSs) in the context of new-generation intelligent manufacturing. *Engineering*, 5, pp 624–636.

[12] **Chucheep, T., Mahathaninwong, N., & Janudom, S.** 2020. The cost benefit analysis of improved wear band saws. *The South African Journal of Industrial Engineering*, 31(1), pp 1–11.

[13] **Liu, X. & Wang, P.** 2022. Valuation of continuous monitoring systems for engineering system design in recurrent maintenance decision scenarios. *Journal of Mechanical Design*, 144(091702), pp 1–12.

[14] **Bank of Thailand (BOT).** 2024. Daily foreign exchange rates [Online] Available at https://www.bot.or.th/th/statistics/exchange-rate.html [Accessed Apr 4, 2024].

[15] **Corley, R.H.V. & Tinker, P.B.** 2016. *The oil palm*, 5th ed. West Sussex: Wiley Blackwell.

[16] **Purnama, K.O., Setyaningsih, D., Hambali, E., & Taniwiryono, D.** 2020. Processing, characteristics, and potential application of red palm oil: A review. *International Journal of Oil Palm*, 3(2), pp 40–55. https://doi.org/ 10.35876/ijop.v3i2.47

[17] **Wenten, I.G., Victoria, A.G., Tanukusuma, G., Khoiruddina, K., & Zunita, M.** 2019. Simultaneous clarification and dehydration of crude palm oil using superhydrophobic polypropylene membrane. *Journal of Food Engineering*, 248, pp 23–27.

[18] **Obibuzor, J.U., Okogbenin, E.A., & Abigor, R.D.** 2012. 11 — Oil recovery from palm fruits and palm kernel. In: Lai, O.-M., Tan, C.-P., Akoh, C.C. (eds.), *Palm oil: Production, processing, characterization, and uses.* Urbana AOCS Press, pp. 299–328. https://doi.org/10.1016/B978-0-9818936-9-3.50014-9

[19] **Hermantoro, H., Ruswanto, A., Gunawan S., & Putra, A.P.** 2024. Fresh fruit bunch (FFB) processing modification to increase crude palm oil (CPO) rendement. *The 5th ICAGRI 2023 IOP Conference Series: Earth and Environmental Science,* 1297, 012084. https://doi:10.1088/1755-1315/1297/1/012084

[20] **Chew, C.L., Yong Ng, C., Hong, W.O., Wu, T.Y., Lee, Y.Y., Low, L.E., Kong, P.S., & Chan, E.S.** 2021. Improving sustainability of palm oil production by increasing oil extraction rate: A review. *Food and Bioprocess Technology*, 14, pp 573–586. https://doi.org/10.1007/s11947-020-02555-1

[21] **ANSAMOTION**. 2024. *RS485-LORA-M product manual*. [Online] Available at https://www.amsamotion.store/wp-content/uploads/2022/09/RS485-LoRa-Muser-manual_ver 1.0.pdf?srsltid=AfmBOorb27H8qIqZ-qgdMft8SuSQXVu3F5RkQN8by9gqSVy4uWl3U2tx [Accessed May 9, 2024].

[22] **May, A. & McMillan, D.** 2013. Condition based maintenance for offshore wind turbines: The effect of false alarms from condition monitoring system. [Online] Available at http://strathprints.strath.ac.uk/45782/

[23] **Wondi, M.H., Haris, N.I.N., Shamsudin, R., Yunus, R., Ali, M.M., & Iswardi, A.H.** 2024. Development and testing of an oil palm (*Elaeis guineensis* Jacq.) fruit digester process for kernel free in crude palm oil production. *Industrial Crops & Products*, 208, 117755. https://doi.org/10.1016/j.indcrop.2023.117755

[24] **Matyas, K., Nemeth, T., Kovacs, K., & Glawar, R.** 2017. A procedural approach for realizing prescriptive maintenance planning in manufacturing industries. *CIRP Annual Manufacturing Technology,* 66, pp 461–464. https://doi.org/10.1016/j.cirp. 2017.04.007

[25] **Fasth-Berglundand, Å. & Stahre, J.** 2013. Cognitive automation strategy for reconfigurable and sustainable assembly systems. *Assembly Automation*, 33(3), pp 294 –303.

[26] **Rossit, D.A., Tohmé, T., & Frutos, M.** 2019. An Industry 4.0 approach to assembly line resequencing. *The International Journal of Advanced Manufacturing Technology*, 105, pp 3619–3630. https://doi.org/10.1007/s00170-019-03804-0

[27] **Firdaus, M., Salleh, S.M., Nawi, I., Ngali, Z., Siswanto, W.A., & Yusup, E.M.** 2016. Preliminary design on screw press model of palm oil extraction machine. *IOP Conference Series: Materials Science and Engineering*, 165, 012029. https://doi:10.1088/1757-899X/165/1/012029

[28] **Nadzim, U.K.H.M., Yunusb, R., Omar, R., & Lim, B.Y.** 2020. Factors contributing to oil losses in crude palm oil production process in Malaysia: A review. *International Journal of Biomass & Renewables*, 9(1), pp 10–24.

[29] **Groover, M.P.** 2015. *Automation, production systems, and computer-integrated manufacturing*, 4th ed. New Jersey: Pearson Education.

[30] **Ministry of Industry.** 2019. The achievement in implementation of the government policy and industrial strategy fiscal year 2019. [Online] Available at https://www.industry.go.th/web-upload/1xff0d34e409a13ef56eea54c52a291126/m_magazine/12668/366/file_download/3791a5286 7e7680d42e68172d9cbaeb1.pdf [Access May 9, 2024]

[31] **Kandiah, S., Basiron, Y., Suki, A., Taha, R.M., Hwa, T.Y., & Sulong, M.** 2006. Continuous sterilization: The new paradigm for modernizing palm oil milling. *Journal of Oil Palm Research* (Special Issue – April 2006), pp 144–152.

[32] **Subramaniam, V., Menon, N.R., Sin, H., & May, C.Y.** 2013. The development of a residual oil recovery system to increase the revenue of a palm oil mill. *Journal of Oil Palm Research,* 25(1), pp 116–122.