

## Conceptual design improvement and assessment of an oil palm harvesting machine via computer-aided design software

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### Abstract

The current design of the harvesting machine exhibits limitations in terms of efficiency and operational cost. The existing track system, cart configuration, and lack of flexibility in the harvesting tool hinder optimal performance. To address these issues, this research aimed to propose and evaluate three design improvements: transitioning from a track system to tyres, integrating a six-axis robotic arm, and separating the cart system. The study utilised Computer-Aided Design (CAD) software for detailed modelling and visualisation of the proposed designs. A basic economic analysis was also done to study the impact of design improvement on the machine's operational cost. When the track system changed to tyres, the travelling speed increased to 3.5 times that of the current speed, i.e., 13 km/h. The cart was separated into an additional chassis so the centre of mass could be maintained at the proper position. The six-axis robotic arm added flexibility to the harvesting tool. Economic analysis indicated that the new machine design had a lower operational expenditure (OPEX), i.e., RM58.94 compared to RM60.78, although the price of the new machine was RM100,000 higher. It can be concluded that the new design improvements using CAD software could be used to assess the machine's viability without constructing a physical prototype.

## 1. Introduction

After centuries of cultivating oil palm as a commodity, the development of technology, especially regarding mechanised plantation operations, has proven to be highly challenging. The most challenging and troublesome task on oil palm plantations is harvesting due to the palm trees' height and numerous sharp thorns, as well as their fronds' fibrosity, which gives them high elasticity (Guturu and Vidhan, 2015; Khalid *et al.*, 2015; Ooi *et al.*, 2017). Despite such challenges, oil palm remains the main commodity crop for Malaysia, with export revenue exceeding RM67.12 billion in 2018 (Ghulam Kadir 2020).

To address the issue of oil palm fresh fruit bunch (FFB) harvesting, especially from tall palm trees, many attempts have been made to engineer a mechanised harvester, the main goal of which was to increase the productivity yield and reduce the workforce size. The Malaysian Palm Oil Board (MPOB) introduced its version of a tall palm harvesting machine, which began development in 1989 (Mohd Ramdhan and Abd Rahim 2014). Figure 1 shows the harvesting machine operating on an oil palm plantation.



Figure 1. A harvesting machine developed by MPOB.

Harvesting is a very important activity in oil palm plantations. Cheap and efficient harvesting processes are factors that ensure good returns. Efficient mechanical harvesting of oil palm fresh fruit bunch (FFB) remains an issue that needs to be addressed. The current methods of harvesting involve the use of a chisel or sickle, which require manual labour and are therefore tedious. Machine performance in terms of productivity and cost-effectiveness was monitored. It was found that the productivity of the machines ranged from 3 to 6 tonnes per day, depending on various factors. However, the

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economic analysis shows that the cost per tonne for a mechanical harvesting machine was slightly higher than compared of manual operation. It is envisaged that with the successful introduction of the mechanical harvester, opportunities for new technologies would open up for the development of more efficient and cheaper machines in the future.

The machine was unfortunately not widely accepted by the oil palm industry due to its high operational costs compared to the productivity yield. Moving the machine from palm to palm was difficult because of the stability issues it encountered due to its design, while its usage of a small radius track system was another factor that contributed to the machine's low acceptance rate (Nur *et al.*, 2014). Therefore, there is considerable scope for improving and developing the machine to make it more effective and efficient when it is used in the oil palm industry. Improving the mechanical system, for example, would serve as an initial optimisation step to further enhance the machine's performance (Figueredo and Sansen, 2014). This paper proposes an improved design to increase the efficiency and performance of the machine using Computer-Aided Design (CAD) software. Mechanical design improvements, like enhanced precision and speed, optimised resource use, and reduced maintenance downtime, directly elevate harvesting machine efficiency and performance. These advancements, vital for oil palm plantation operations, boost throughput by increasing speed and precision, while minimising downtime. Improved resource use and reduced maintenance enhance overall operational efficiency, directly impacting harvesting productivity, improving yields, and bolstering cost-effectiveness. A design analysis review was performed to verify the viability of this design improvement.

## 2. Materials and methods

The current design of the harvesting machine exhibits limitations in terms of efficiency and operational cost. The existing track system, cart configuration, and lack of flexibility in the harvesting tool hinder optimal performance. To address these issues, this research aims to propose and evaluate three design improvements: transitioning from a track system to tyres, integrating a six-axis robotic arm, and separating the cart system. The objectives are to enhance the machine's speed, maintain the centre of mass appropriately, and introduce flexibility in the harvesting process. The proposed design was improved with the aid of the CAD software SolidWorks, the aim of which was to produce a 3D model of the corresponding improvement so it could be further analysed using the analysis tools available in the same software. With the aid of the software, the need to

physically produce a prototype of the improved design could be avoided, thus saving cost and time during the machine's research and development stage (Ramli *et al.*, 2020).

Three design improvements to the current harvesting machine were made to achieve the main goal of enhancing the machine's efficiency and capability. Mechanisation on plantations has been widely recognised as being more expensive compared to the conventional method (Azman and Simeh 2012). It was assumed that by enhancing the machine's efficiency and capability, the productivity yield would increase, and, consequently, the plantation's operational costs would be reduced. The proposed improvements to the harvesting machine are listed in Table 1. To address these issues, this research aims to propose and evaluate three design improvements: transitioning from a track system to tyres, integrating a six-axis robotic arm, and separating the cart system. The objectives are to enhance the machine's speed, maintain the centre of mass appropriately, and introduce flexibility in the harvesting process.

Table 1. Proposed improvements to the harvesting machine.

Proposed Improvement	Description
1) Replacement of the track system with bigger tyres	<ul style="list-style-type: none"> <li>• Larger tyres to increase the speed and agility of the machine</li> </ul>
2) Separation of the cart into a detachable chassis	<ul style="list-style-type: none"> <li>• Enhances stability and loading capacity</li> </ul>
3) Addition of a six-axis robotic arm	<ul style="list-style-type: none"> <li>• Enhances flexibility when manoeuvring the harvesting tool</li> </ul>

Each proposed improvement was established in 3D, and the viability of the designs - such as the calculations of the machine's centre of mass, movement simulation and measurement evaluation - was checked using SolidWorks. Higher speed allows the machine to cover more ground, reducing downtime and increasing overall efficiency. The versatility of the six-axis robot arm ensures precise and adaptable FFB harvesting in tight spaces between fronds while minimising damage to the fruit and trees. In addition, larger FFB bin capacity enables continuous operation, reducing unloading frequency and optimising harvesting time. These improvements contribute to increased throughput, cost efficiency, and overall improved economic performance for the plantation's operation. In this study, the acceptable dimension of the machine can at least manoeuvre between two palm trees 10 m wide apart in a row and diagonally. The weight of the machine is not specifically restricted in general, but ideally, the machine should not sink and get stuck in the soft ground.

To increase the flexibility and manoeuvrability of the harvesting tool, the plan was to install a six-axis robotic

arm on the harvesting machine. Multiple-axis robotic arms have been widely adopted in the manufacturing industry and tasked with various operations - such as picking, loading, unloading and rotating - using their kinematic capability (Chen and Chang, 2020). This type of robot is also known as a Collaborative Robot or COBOT, which is specifically designed for direct human-robot interaction when the robot and human are in proximity (El Zaatari et al., 2019). In this study, only the mechanical manoeuvring capability is considered and the flexibility of the six-axis arm is needed in harvesting oil palm FFB. The manufacturing technology is possible to be adopted in a plantation environment if its Ingress Protection level (IP) rating is upgraded to suit the outdoor environment. Based on the literature, the adoption of a COBOT could increase productivity by up to 30% more than the conventional method (Galín et al., 2020). Therefore, it was envisaged that the application would also be suitable to be implemented for oil palm harvesting purposes.

To assess the efficiency of the new design, an economic analysis was undertaken by calculating its total daily Operational Expenditure (OPEX) and comparing this with the OPEX of the existing design. The OPEX calculation was based on the work of Stanners and George (1992), who stated that a lower OPEX value would increase the probability that a given technology would be adopted by the industry. The OPEX values were based on the following formulae:

$$OPEX = \frac{\lambda_f + \lambda_l + \lambda_{RM} + \delta}{\sigma_p} \tag{1}$$

$$\delta = \frac{C_{machine}}{\Delta D} \tag{2}$$

The fuel cost,  $\lambda_f$  plus the labour cost,  $\lambda_l$  plus the maintenance and repair costs,  $\lambda_{RM}$ , plus the depreciation value,  $\delta$ , was divided by the productivity in tonnage per day,  $\sigma_p$ . The value of  $\delta$  is equal to the price of the machine,  $C_{machine}$  divided by the total of working days,  $\Delta D$ . When determining the OPEX of the new and improved harvesting machine design, it was assumed that it could achieve a productivity increase of 30%, as mentioned in the literature related to the use of robotic arms in operations (Galín et al., 2020). Some values used in the calculation - such as the economic life, productivity, labour cost and fuel consumption - were based on the literature related to harvesting machines (Mohd Ramdhan and Abd Rahim, 2014).

### 3. Results and discussion

The results of the design analysis of each proposed improvement are presented as follows:

#### 3.1 Replacement of the track system with tyres

The most important aspect to consider when making the design improvement was to retain the machine's stability. This goal was achieved by keeping the machine's centre of mass within its limited range to avoid it tipping over during its operation. Figure 2 depicts a stable simplified harvesting machine, whereas Figure 3 depicts an unstable model with a tendency to flip.

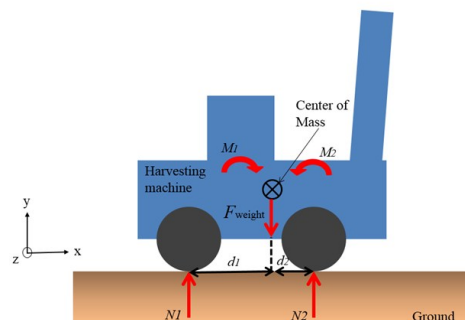


Figure 2. Simplified diagram of a stable harvesting machine.

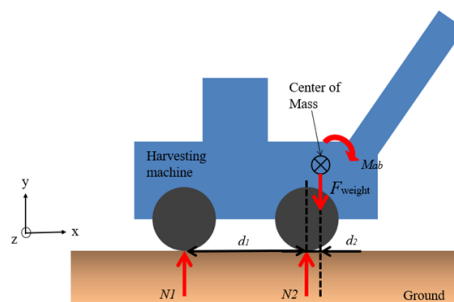


Figure 3. Simplified force diagram showing the forces acting on the machine.

When the track system was changed to tyres, the machine was supported by two contact points where the tyres touched the ground, labelled as  $N1$  and  $N2$  (Figure 2). These points are tangent points between a tyre and the ground. It is determined by the intersection of the tyre's contact patch with the ground. The contact patch is the portion of the tyre that makes direct contact with the road or surface. Understanding and controlling the tangent point is essential for optimising vehicle performance, stability, and traction. Since the machine's centre of mass was between  $N1$  and  $N2$ , this resulted in moments,  $M1$  and  $M2$ , being produced at the pivot points  $N1$  and  $N2$  as follows:

$$M_1 > M_2 = F_{weight} \cdot d_1 > F_{weight} \cdot d_2 \tag{3}$$

Based on Equation 3, the moment at pivot point  $N1$  was larger than the moment at pivot point  $N2$  as the distance between the force produced by the weight from the machine's centre of mass,  $F_{weight}$  and the pivot point  $d_1$  was greater than the distance between  $F_{weight}$  and the pivot point at  $N2$ . However, the resultant moment acted between the two supports,  $N1$  and  $N2$ , so the machine

suffered no instability. A machine is considered unstable when its centre of mass is located beyond the ground's normal contact points because this configuration introduces an inherent risk of tipping and loss of stability. Engineers and designers aim to ensure that the centre of mass remains within the base of support to maintain the machine's stability and prevent potential hazards during operation.

The position of the centre of mass, however, shifted every time the boom changed position. Figure 3 shows an example where the machine's centre of mass shifted beyond the contact point  $N2$ . The simplified force diagram is used to analyse the stability of machinery. By depicting gravitational forces and external factors, the diagram illustrates how shifts in the centre of mass can lead to tipping and instability. When the centre of mass moves beyond the machinery's base of support, a resultant moment is created, inducing a torque that may cause tipping. An equation is based on the consideration that at equilibrium, the total sum of moments at any point is zero. As a result, moment  $M_{ab}$  was produced at the pivot point  $N2$ , as described in Equation 4:

$$\Sigma M_{ab} = N1 \cdot d_1 + F_{\text{weight}} \cdot d_2 \quad (4)$$

The moment  $M_{ab}$ , produced at  $N2$ , was enough to cause the machine to tip forward, which therefore caused the machine to be unstable when the boom was in operation. For that reason, the position of the machine's centre had to be checked whenever a new design was added. Figure 4 shows the new harvesting machine design with the tyres, for which it was confirmed that the centre of mass was between contact points  $N1$  and  $N2$ ; therefore, the machine with the new tyres was able to maintain its stability.

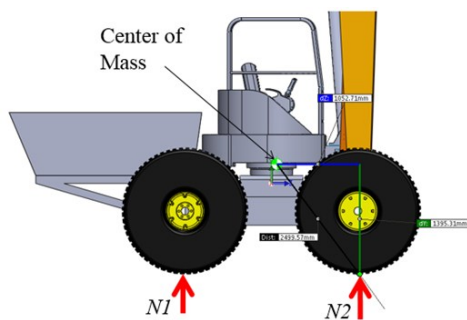


Figure 4. A harvesting machine using tyres.

Another advantage of replacing the track system with tyres was that the machine's speed could be increased because the wheel diameter increased by about 3.5 $\times$ , from 450 mm to 1560 mm. The dimension was based on 3D design analysis, where a suitable size can be verified so that it would not obstruct or hinder any movement or other mechanism. Alterations in the size, which also lead to an increase in material composition mass, influence traction and friction with the ground. The augmented mass may enhance the frictional force

between the wheels and the surface, improving traction. This can be particularly advantageous for stability and control, especially in challenging terrains. The correlation between speed ratio and wheel diameter ratio can be explained using the basic principles of rotational motion. The linear speed of a point on the edge of a rotating object, like a wheel, is given by the product of its angular velocity and the radius of the wheel. Mathematically, this relationship is expressed as:

$$V = \omega \cdot R_{\text{wheel}} \quad (5)$$

Where  $V$  is linear speed,  $\omega$  is angular velocity, and  $R_{\text{wheel}}$  is the wheel's radius. It was considered that two wheels with different diameters were  $d_{\text{new wheel}}$  and  $d_{\text{current wheels}}$ , and their corresponding linear speeds of current speed,  $V_{\text{current}}$  and new speed,  $V_{\text{new}}$ . The speed ratio,  $SR$  is defined as the ratio of these linear speeds:

$$SR = \frac{V_{\text{current}}}{V_{\text{new}}} \quad (6)$$

$$SR = \frac{d_1 \cdot \omega_{\text{current}}}{d_2 \cdot \omega_{\text{new}}} \quad (7)$$

The angular velocity of both wheel diameters was assumed to be the same since they were both connected by the powertrain system with the same motor power. Therefore, the new speed,  $V_{\text{new}}$  was calculated using Equation 8:

$$V_{\text{new}} = \frac{d_{\text{new wheel}}}{d_{\text{current wheel}}} \cdot V_{\text{current}} \quad (8)$$

$d_{\text{new wheel}}$  was set to 1560 mm, whereas  $d_{\text{current wheel}}$  was 450mm. The machine's initial speed was 3.7 km/h. Based on Equation 8, when the track system was changed to 1560mm-diameter tyres, the machine's new speed was roughly 13 km/h. Increasing the travel speed of a harvesting machine enhances operational efficiency and productivity. The higher speed allows the machine to cover more ground within a given timeframe, reducing non-productive downtime and optimising the overall harvesting process. This time efficiency is crucial for timely harvesting, preventing overripening or deterioration of crops and positively impacting crop quality and yield. Moreover, the increased speed contributes to cost efficiency by potentially reducing labour costs and fuel consumption per unit of harvested area, making it a valuable enhancement for agricultural operations. Figure 5 shows the diameter of the harvesting machine's tyres. Bigger tyres also have a bigger contact surface area with the ground, thus reducing ground pressure and able to reduce the possibility of tyres sinking and getting stuck in the ground. This expanded contact area reduces ground pressure, distributing the machine's weight more effectively. As a result, the likelihood of the tyres sinking into soft or uneven terrain is reduced. Lower ground pressure enhances the machine's ability to navigate challenging surfaces by

minimising soil disturbance and sinking, thereby preventing instances of getting stuck. This improved stability and traction provided by larger tyres enhance the overall agility of the machine, allowing it to manoeuvre more effectively in various terrains without compromising performance or being hindered by challenging ground conditions.

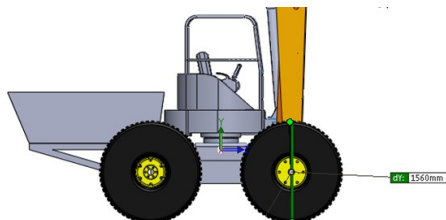


Figure 5. Measurement of the tyres on the harvesting machine.

### 3.2 Separation of the cart into a detachable chassis

The harvesting machine was further analysed to verify its viability and stability. The telescopic boom design was stretched to its maximum height, and different boom operation angles were set before checking the position of the machine's centre. The machine's centre of mass began to shift beyond the *N2* point limit when the boom was at  $26.77^\circ$  from the horizontal. This meant that when the boom was operated at an angle of less than  $26.77^\circ$  from the horizontal, the machine lost its stability and had a tendency to tip over. Figure 6 shows the position of the machine's centre of mass when the boom was set at  $26.77^\circ$  from the horizontal. Based on the measurement evaluation, the machine's centre of mass shifted about 33 mm to the right from *N2* and started to create a moment at the *N2* pivot point.

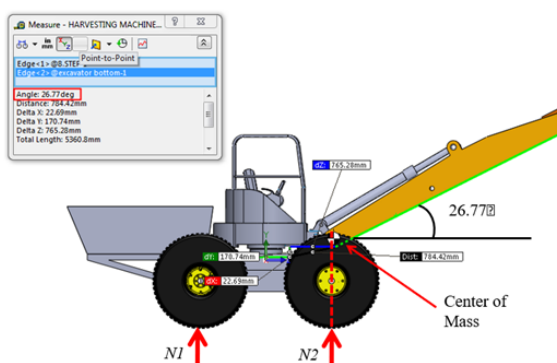


Figure 6. Shift in centre of mass which caused the machine's

A separate cart with a detachable chassis was proposed to eliminate the instability. The new cart could shift the centre of mass further to the left to avoid the machine tipping over due to the boom's position. In addition, the separate cart also enabled the cart capacity to be increased to twice that of the current attached cart without jeopardising the machine's stability. Figure 7

shows the new design with the separate cart and the position of the new centre of mass.

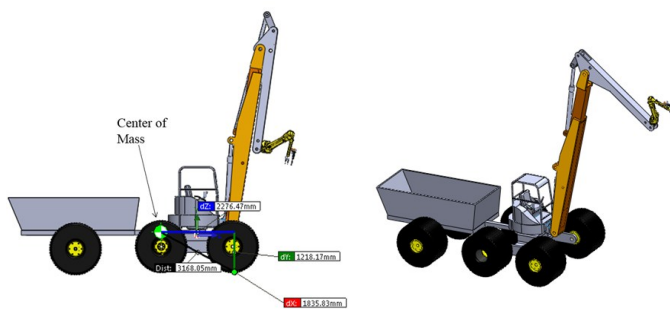


Figure 7. Shift in the machine's centre of mass with the new cart design.

The stability of the new design was rechecked using the SolidWorks mass property tool by identifying the position of the new centre of mass. The boom was extended again to its maximum at different angle variations. The centre of mass of the machine was found not to exceed the *N2* contact point at any angle variation, even when the boom was set at the horizontal (Figure 8). This meant that theoretically, the new design would experience no instability issues and would not tip over.

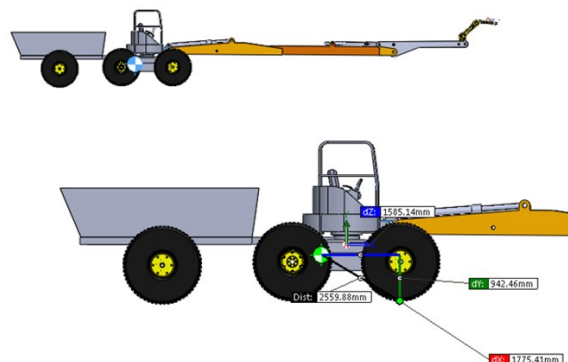


Figure 8. Shift in machine's centre of mass when the boom was set at the horizontal.

### 3.3 Addition of a six-axis robotic arm

Figure 9 illustrates the proposed design of a harvesting machine with a six-axis robotic arm system. A six-axis robotic arm system was attached to the end of the boom, and the system was installed with a harvesting tool, a 3D depth camera and a grabber to take the harvested FFB (Figure 9). Figure 10 shows a detailed view of the six-axis robotic arm system and the accessories installed (the harvesting tool, depth camera and grabber).

The six-axis robotic arm had the capability to manoeuvre a harvesting tool along the translation axes of *x*, *y* and *z*, as well as to rotate the tool along the *x*, *y* and *z* axes. This allowed the harvesting tool to be handled freely in all possible ways, so it could be placed in the right position in the tight gaps between the FFB and the fronds. Other than using the scissor mechanism as a

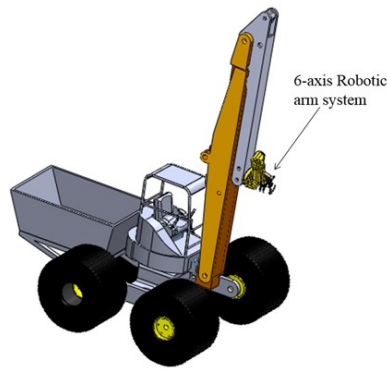


Figure 9. Harvesting machine design with a six-axis robotic arm system.

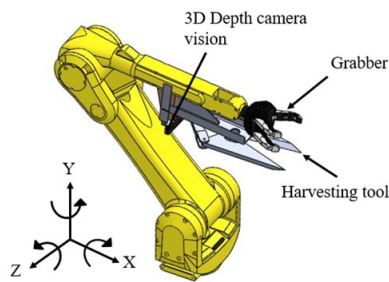


Figure 10. A six-axis robotic arm system with accessories.

harvesting tool, other possible harvesting tools, like an ultrasonic cutter or a laser system, could also be placed on the robotic arm (Singh *et al.*, 2016; Azaman *et al.*, 2020). The range of motion for this arm is  $300^\circ$ , and the effective range of motion for harvesting FFB is  $45^\circ$  based on the arm's technical specification, as illustrated in Figure 11.

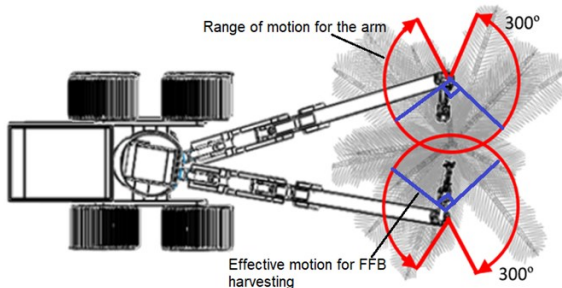


Figure 11. The range of motion and effective range for FFB harvesting of robotic arm.

A grabber was attached to the robotic arm so it could grab the FFB once it had been cut with the harvesting tool, thus preventing the FFB from falling to the ground. This would reduce the number of loose oil palm fruits, which usually result from the impact of the FFB falling to the ground. The FFB quality might also be retained as the impact of the FFB falling to the ground is known to reduce the quality of oil produced, while it may also expose the oil palm to the contaminant 3-monochloro-1,2-propanediol fatty acid esters (3-MCPD esters) (Matthäus *et al.*, 2011), which is caused by the use of fertilisers containing chloride salts (Santiago *et al.*, 2021). Therefore, the application of the grabber

mechanism could prevent the FFB from falling to the ground and thus avoid any contact with the fertiliser containing the 3-MCPD contaminant.

In addition, the robotic arm was equipped with a 3D depth camera so it could provide a 3D scan of the condition and structure of the palm crown, as well as accurately map the position of the FFB and the fronds. With this technology, the machine operator could easily assess the position of those objects, and the movement of the harvesting tool between the tight gaps of the FFB stalks could be facilitated. Figure 12 depicts the flexibility of the robotic arm in manoeuvring a harvesting tool.

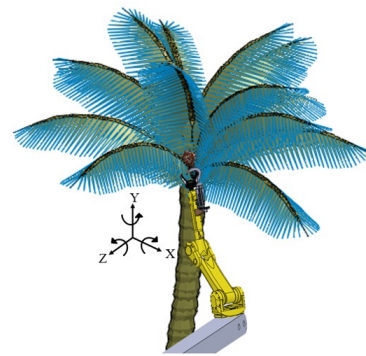


Figure 12. A six-axis robotic arm system harvesting an FFB.

The machine was able to reach up to 15 metres with the new boom design featuring the robotic arm system. The robotic arm also provided the harvesting tool with the flexibility to locate and harvest FFB from any position around the palm crown without the need to move the whole machine. Figure 13 shows the height attained by the current harvesting machine and the new boom design, as well as a top-down view of the space assessment of the machines while manoeuvring the cutting tool around the palm crown. The space assessment simulation showed that the machine could be in a fixed position in front of the palm tree and still reach any FFB around the palm tree crown.

Next, economic analysis was undertaken to determine the efficiency of the new design. Table 2 lists the details and related values used in this analysis, as well as the OPEX calculation for both the current and new harvesting machine designs (Mohd Ramdhan and Abd Rahim, 2014).

For the economic analysis calculation, it was assumed that the whole design improvement and the addition of the six-axis robotic arm would incur an extra RM100,000 in terms of the cost of the machine. The robot arm price was based on the current market price review done during the study. This also reflected the higher repair and maintenance cost, which was estimated to increase to RM150 daily on average, compared to RM100 previously. The productivity of the new design

was estimated to increase by 30% to 7.8 tonnes/man-day, based on the productivity increment due to the operational use of the COBOT, as stated in the literature (Galín et al., 2020).

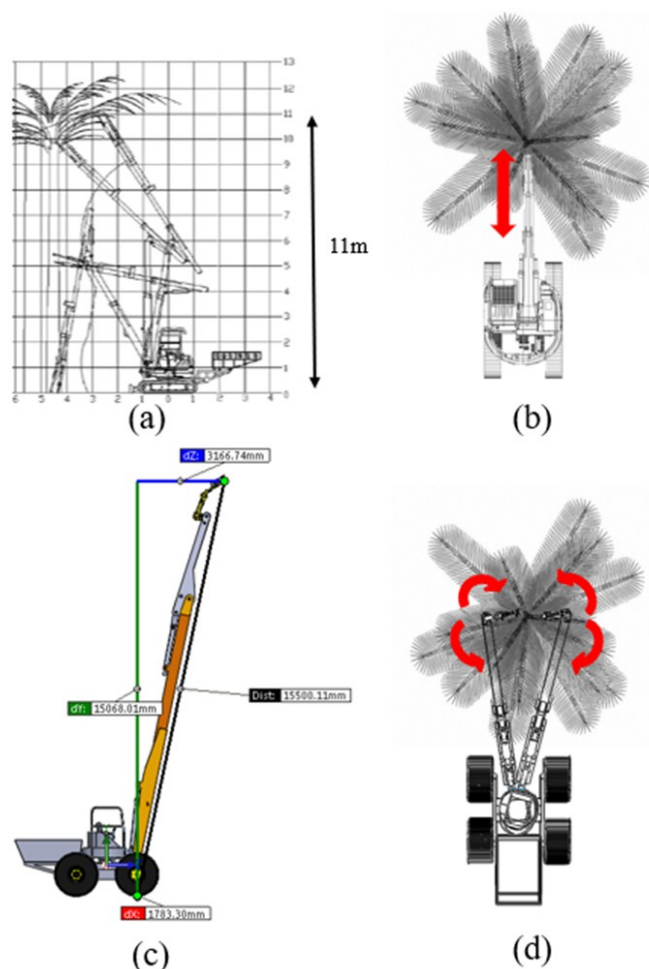


Figure 13. (a) The maximum reach of the harvesting machine, (b) the accessible space of the harvesting machine’s boom, (c) the maximum reach of the new harvesting machine and (d) the accessible space of the new harvesting machine’s boom.

Table 2. Economic analysis of existing and new harvesting machine designs.

Details	Existing Harvester	New Harvester
Machine Price (RM)	280,000	380,000
Economic life (Years)	6	6
Productivity (tonnes/man-day)	6	7.8
Number of working days per year	300	300
Machine’s depreciation (RM/day)	166	211
Labour Cost (RM/day)	60	60
Fuel Consumption (L/day)	18	18
Fuel cost per day (RM/day)	38.70	38.70
Repair and Maintenance cost (RM/day)	100	150
Total Operation Cost (RM)	364.70	459.70
Cost per Tonne / OPEX (RM/)	60.78	58.94

Therefore, the OPEX values calculated for the existing and new harvesting machine designs were

RM60.78/tonne and RM58.94/tonne, respectively, by dividing the total operation cost by the total productivity. This clearly shows that although the new machine design included extra electronics and robotics systems, which are known to be expensive and to add high extra costs, especially during the acquisition phase, in the long term, the OPEX of adopting such technology was slightly lower than the value obtained for using the conventional system. From this economic analysis, the productivity increase due to the adoption of robotics technology and several design improvements was shown to contribute to lowering the OPEX when using the machine. This demonstrates the importance of an oil palm harvesting machine to achieve a certain productivity level to compensate for the high price of adopting any suitable technology. Figure 14 depicts the linear relationship between the cost of a harvesting machine against the productivity efficiency it must achieve to maintain the OPEX of RM60/tonne if the current harvesting machine’s OPEX were taken as the benchmark for this study.

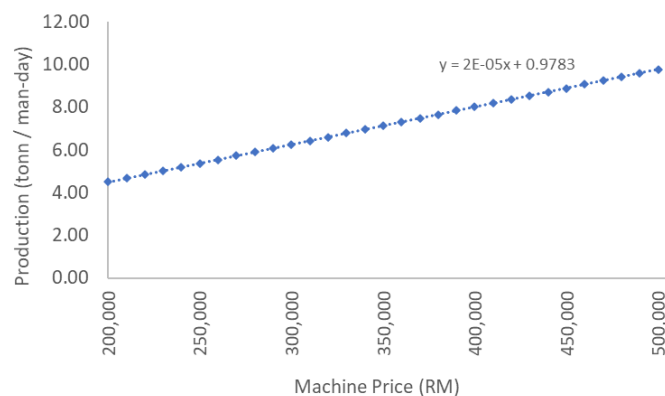


Figure 14. The relationship between the harvesting machine cost against the productivity efficiency it must achieve to maintain the OPEX of RM60/tonne.

In determining the relationship between the machine cost and the required productivity output, an estimated daily increase of RM5 for repair and maintenance costs was assumed for every RM10,000 increase in the total machine price, based on the study undertaken to estimate the repair and maintenance cost evaluation of this machine. Hence, a general equation model to estimate the required productivity output for a corresponding cost of an excavator-based oil palm harvesting machine can be given as follows:

$$\sigma_p = 2 \times 10^{-5} \cdot C_{machine} + 0.9783 \tag{9}$$

Thus, the required output for an oil palm harvesting machine is directly proportional to the machine cost. The higher the price of the machine, the greater the productivity output required to maintain a lower OPEX during oil palm plantation operations.

It was also found that with the increase in

productivity, the OPEX of the machine was able to be reduced up to a point where the OPEX of the current machine is almost the same as the new harvesting machine design, even though the price of the latter is 35% higher. Figure 15 depicts the relationship between OPEX versus the productivity of both versions of the harvesting machine.

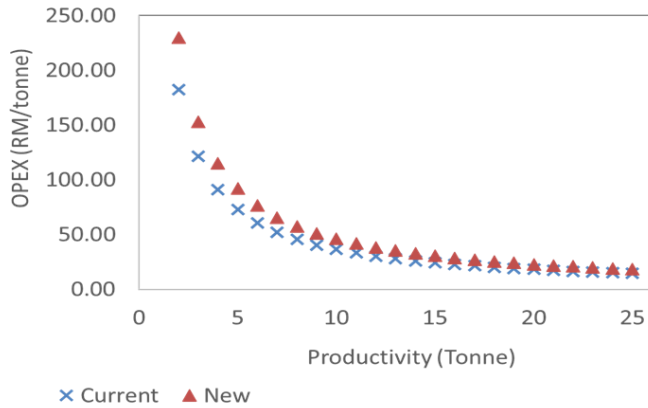


Figure 15. The relationship between the OPEX and the productivity of the harvesting machine.

Based on Figure 15, it can be clearly seen that once the machine is able to achieve up to 20 to 25 tonnes of FFB harvested per day, the OPEX of the machine can be significantly reduced up to RM 19.00/tonne on average. Therefore, it is very important that the harvesting machine is upgraded to a level where it can achieve high harvesting efficiency and increase its productivity so that the OPEX for running the machine in plantations is attractive enough to the industry players.

#### 4. Conclusion

In conclusion, CAD software played a crucial role in assessing and verifying the viability of three major improvements to the harvesting machine: replacing the track system with tyres, installing a six-axis robotic arm, and separating the cart section into a different chassis. These enhancements significantly increased the machine's performance, with the tyre system improving travel speed by up to 3.5 times and the new cart design ensuring stability even when the boom was fully extended horizontally. The addition of the robotic arm provided greater flexibility, allowing precise manoeuvring of the harvesting tool around the palm crown from a fixed machine position. CAD simulations confirmed the mechanical feasibility of these upgrades, while economic analysis showed that despite an increased capital cost of up to RM100,000, the improved machine reduced operating expenses to RM58.94/tonne due to a 30% boost in productivity. A general mathematical model was also developed to predict the required productivity levels needed to maintain current OPEX values with rising machine costs. However, the

analysis has limitations, including simplifications in statics, kinematics, and dynamics, potential oversights of real-world variables, and lack of empirical testing. These constraints highlight the need for further research and field validation to ensure the improved design performs reliably under practical conditions.

#### Conflict of interest

The authors declare no conflict of interest.

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