Rubber (Latex) Cutting Process Considering the Cost of the Double Cut Alternative (DCA) Process in Human and Robot Collaboration

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ABSTRAK

Perkembangan teknologi memungkinkan dilakukannya kolaborasi sumber daya manusia-robot dalam proses pemotongan karet (lateks) di perkebunan. Kegiatan kolaborasi manusia-robot dilakukan secara bersamaan pada masing-masing pohon karet namun mempunyai tugas kerja yang berbeda-beda. Penelitian mengenai biaya sumber daya kolaborasi manusia-robot pada kegiatan proses pemotongan karet (lateks) masih minim, sehingga perlu dilakukan pembahasan dan perhitungan biaya sumber daya kolaborasi manusia-robot dengan mengembangkan model matematika. Penelitian mengenai biaya sumber daya kolaborasi manusia-robot pada proses pemotongan karet (lateks) masih minim, sehingga diperlukan pembahasan dan perhitungan dengan pengembangan model matematika. Pengembangan model matematika bukan sekedar latihan teoritis. Tujuan praktisnya adalah meminimalkan biaya dengan mempertimbangkan sumber daya manusia, robot, dan kolaborasi manusia-robot. Melalui pengujian yang ketat, kami bertujuan untuk minimalisasi biaya dari setiap sumber daya. Hasil pengujian menunjukkan sumber daya kolaborasi manusia-robot dapat mempengaruhi biaya minimasi secara signifikan. Biaya minimasi diselesaikan dengan membuat program algoritma dalam perangkat lunak optimasi. Program ini digunakan untuk menghasilkan biaya minimasi dengan waktu yang relatif cepat yang mengacu pada diagram prioritas proses pemotongan karet (lateks). Berdasarkan hasil data eksperimen, pengembangan model matematis berfungsi secara logis untuk memecahkan permasalahan penempatan sumber daya, menghasilkan biaya minimasi sebesar IDR 1,618,234,564.595, total sumber daya manusia sebanyak 1 orang dan sumber daya robot sebanyak 1 unit.

Kata kunci: *kolaborasi manusia-robot, model matematika, tugas, alokasi.*

ABSTRACT

Technological developments allow human-robot collaboration resources to be carried out in the rubber (latex) cutting process in plantations. The human-robot collaboration activities are carried out simultaneously in each rubber tree but have different work tasks. Research regarding human-robot collaboration resource costs in the rubber (latex) cutting process activity is still minimal, so it is necessary to discuss and calculate the resource costs of human-robot collaboration by developing mathematical models. Research regarding the resource costs of human-robot collaboration in the rubber (latex) cutting process is still minimal, so discussion and calculations are needed with the development of mathematical models. Mathematical model development is not just a theoretical exercise. The practical goal is to minimize costs by considering human resources, robots, and human-robot collaboration. Through rigorous testing, we aim to minimize the cost of each resource. Test results show that human-robot collaboration resources can significantly influence cost minimization. Cost minimization is accomplished by programming an algorithm in optimization software. This program is used to make it easier to complete the optimal solution in terms of relatively fast time, which refers to the precedence diagram of the rubber (latex) cutting process. Based on the results of experimental data, the development of a mathematical model functions logically to solve resource placement problems, resulting in a minimum cost of IDR 1,618,234,564.595, total human resources of 1 person and robot resources of 1 unit.

Keywords: *human robot collaboration, mathematical model, assignment, allocation, total cost, dca.*

1. Introduction

The global rubber market production and consumption is estimated to grow at a rate of 2.5% annually, and world trade is estimated to grow at a rate of 2.6% annually, with the price of rubber expected to range from US$1.2 to US$1.5 per kg (Damanik, 2012). This presents a significant opportunity for Indonesia to increase production and export volume, with projections indicating a potential annual growth of 2.2%. Therefore, the government is pursuing agricultural development initiatives aimed at boosting production and income for farmers, with a focus

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on both increasing yields and improving the quality of plantation products. Labor is one of the main production factors (input) which plays a very important role in farming, because it is a driving element for production factors (Rohansyah, 2017).

However, the aging workforce, with many farmers approaching retirement age, coupled with a lack of young talent entering the sector, is a major concern (Ruiz et al., 2022). This lack of young workers has contributed to declining latex yields in rubber plantations and the current rubber tapping process is manual, requiring workers to tap hundreds of trees daily across a one-hectare area (Irfan, 2022). Labor costs for this process average IDR. 1,824,000 per month (Komala, 2017).

The development of robotic technology for the rubber tapping process offers a potential solution. These robots can operate independently, completing the tapping process in just 20 seconds per tree, compared to the 45-50 seconds required by human workers (Faez, 2020). Human-Robot Interaction (HRI) has been explored in the agricultural sector as a way to address complex tasks and leverage the benefits of collaboration between humans and robots (Vasconez et al., 2019). Despite the potential benefits of HRI, limited research exists regarding cost-minimization strategies in the rubber tapping process that consider the combined use of human labor, robots, and HRI approaches. This is likely due to concerns about initial investment costs, ongoing operational expenses, and maintenance requirements, all while ensuring minimal disruption to existing workflows (Varghese et al., 2021).

2. Research Methods

The first reference model (Susanto, 2019) focuses on determine the placement of an operational resource on an assembly line based on process time and provide a solution with the lowest total production cost with a straight assembly line and producing several types of products. This model utilizes the following objective function.

$$Tc = (C_{I1} \times \alpha + C_{I2} \times \rho + (C_{O1} \times \alpha + C_{I2} \times \rho) \times D \times \tau - \sum_{i=1}^{n_T}(\sum_{j=1}^{n_W} b_{2i}x_{ij2}) - \sum_{i=1}^{n_T}\left(\sum_{j=1}^{n_W} b_{3i}x_{ij3}\right) \quad (1)$$

The second reference (Zhou et al., 2021) focuses on tapping process using robot optimization for rubber cutting and presents the design of a rubber cutting robot for natural rubber plantations and an upgraded spatial spiral trajectory is established by analyzing the trunk and manual rubber cutting trajectories for the operation of a six-axis tandem robot arm.

The cutting process time using a robot is 17.01 ± 3.65 seconds with a rubber tree bark cutting depth of 2.0 mm to 5.0 mm. Then, the accuracy of chip thickness and chip width is 1.73 ± 0.28 mm and 5.07 ± 0.13 mm, respectively, with a chip weight of 1.99 ± 0.24 mm. The average operating time of the entire tapping operation was 80 ± 5 seconds.

$$S_{Full} = \frac{\pi R^2 - \pi(R-\omega)^2}{2} = \frac{\pi\omega_a\,(2R_a-\omega_a)}{2} \quad (2)$$

The third reference model (Zhang et al., 2019) optimizes robot navigation on rubber trees after latex cutting. This model focuses on optimizing navigation with a target speed of 0.3 m/s and incoIDRorates specific goal and function constraints (details below).

$$L_2\,Sin\,(\alpha+\delta), L_2 Cos\,(\alpha+\delta) \quad (3)$$

Proposed Model (Objective Function)

Mathematical model of rubber latex cutting process based on alternative human resources, robot resources, and human-robot collaboration resources with the process of cutting rubber latex from the upper and lower parts of the tree, with a navigation process to each tree that has limitations on working hours, work attendance, maintenance costs, operational costs, and other cost burdens used to maximize the potential of rubber latex products.

$$T_C = C_{IH} * \beta + C_{IR} * \gamma + C_{MR} * \gamma + \left(\frac{(C_{OH}*\beta*H_{dH}*3600*D_{wH})}{\left(\frac{\frac{\pi\omega_a\,(2R_a-\omega_a)}{2}}{V_{LH}}\right)+\left(\frac{\frac{\pi\omega_b\,(2R_b-\omega_b)}{2}}{V_{LH}}\right)}\right) + \left(\frac{L_2 Sin\,(\alpha+\delta), L_2 Cos\,(\alpha+\delta)}{V_{NH}}\right) +$$

$$\left(\frac{(C_{OR}*\gamma*H_{dR}*3600*D_{wR})}{\left(\frac{\frac{\pi\omega_a\,(2R_a-\omega_a)}{2}}{V_{LR}}\right)+\left(\frac{\frac{\pi\omega_b\,(2R_b-\omega_b)}{2}}{V_{LR}}\right)}\right) + \left(\frac{L_2 Sin\,(\alpha+\delta), L_2 Cos\,(\alpha+\delta)}{V_{NR}}\right) - \sum_{i=1}^{n_T}(\sum_{j=1}^{n_W} b_{2i}x_{ij2}) - \sum_{i=1}^{n_T}\left(\sum_{j=1}^{n_W} b_{3i}x_{ij3}\right)\,) \quad (4)$$

Limiting Function

$$P_{PAH} = \left(\frac{\frac{\pi\omega_a\,(2R_a - \omega_a)}{2}}{V_{LH}}\right) \tag{5}$$

$$P_{PBH} = \left(\frac{\frac{\pi\omega_b\,(2R_b - \omega_b)}{2}}{V_{LH}}\right) \tag{6}$$

$$W_{PNH} = \left(\frac{L_2 Sin\,(\alpha+\delta), L_2 Cos\,(\alpha+\delta)}{V_{NH}}\right) \tag{7}$$

$$P_{PAR} = \left(\frac{\frac{\pi\omega_a\,(2R_a - \omega_a)}{2}}{V_{LR}}\right) \tag{8}$$

$$P_{PBR} = \left(\frac{\frac{\pi\omega_b\,(2R_b - \omega_b)}{2}}{V_{LR}}\right) \tag{9}$$

$$W_{PNR} = \left(\frac{L_2 Sin\,(\alpha+\delta), L_2 Cos\,(\alpha+\delta)}{V_{NR}}\right) \tag{10}$$

The mathematical notations as follows:

1. Index

i, h, p	Tasks
j,q	Rubber Tree
s	Alternative Resource (Human = 1, Robot = 2, Human-Robot Collaboration = 3)

2. Parameter

I	Tasks, $I = \{1,2,\dots nT\}$
J	Rubber tree collection, $J = \{1,2,\dots nW\}$
P	The set of task pairs (*h*, *i*) with task h being the direct predecessor of task *i*.
t_{is}	Processing time of task i worked on by resource type *s*.
ω_a	Deep of cut the upper tree
R_a	Radius of the lower tree
ω_b	Deep of cut the lower tree
V_{LH}	Speed cutting of human
V_{LR}	Speed cutting of robot
L	Distance tree *i* to tree *j*
V_{NH}	Speed navigation of human
V_{NR}	Speed navigation of robot
CI_H	Human investment cost
CI_R	Robot investment cost
CO_H	Human operational costs as workers
CO_R	Robot operating costs
b_{2i}	Saving cost due to using robot on task *i*
b_{3i}	Saving cost due to using human-robot collaboration on task *i*
H_{dH}	Hour day of human
D_{wH}	Days a week of human
H_{dR}	Hour day of robot
D_{wR}	Days a week of robot
W_{PnH}	The process time for navigation (tree *i* to tree *j*) human resources.
W_{PnR}	The process time for navigation (tree *i* to tree *j*) robot resources.
PP_{aH}	The process time for tapping the upper part of the rubber sap is a human resource
PP_{bH}	The process time for tapping the lower part of the rubber sap requires human resources.
PP_{aR}	The process time for tapping the upper rubber sap of the robot resource
PP_{bR}	The process time for tapping the rubber sap from the bottom of the robot resource

3. Supporting Variables

β	Total number of workers required on the plantation
γ	Total number of collaborative robots required on the plantation

α Deviation of tree *i*
δ Deviation of tree *j*

4. Decision Variables
x_{ijs} The decision variable of an assignment of task i to tree j with resources (Human = 1, Robot = 2, Human and Robot Collaboration = 3) has a binary value (0,1).

The Equation 1 shows that the objective function focuses on an operational resource on an assembly line based on process time and provide a solution with the lowest total production cost with a straight assembly line and producing several types of products. The Equation 2 shows that the objective function focuses on tapping process using robot optimization for rubber cutting. The Equation 3 shows that the objective function focuses on optimizes robot navigation on rubber trees after latex cutting. The Equations 1, 2 and 3 are reference equations in the Reference Model Modification reference that will be used.

The Equation 4 shows that the objective function to be achieved is to minimize the cost of investment costs, operational costs, maintenance costs and savings that can be made. Operational costs are calculated by multiplying the amount of each type of resource by the operational cost for one type of resource. The Equation 5 and 6 for the process of cutting the upper and lower part of the rubber latex by humans. The Equation 7 for the process of navigation part of the rubber latex by humans. The Equation 8 and 9 for the process of cutting the upper and lower part of the rubber latex by robot. The Equation 10 for the process of navigation part of the rubber latex by robot.

3. Results And Discussion

Numerical testing was conducted to determine the characteristics of the mathematical model derived from the latex cutting process precedence diagram and translated into an optimization application program.

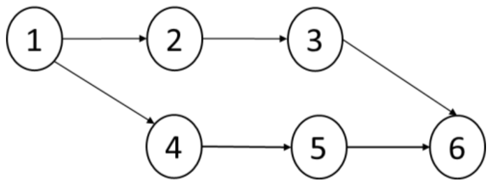

Figure 1. Precedence diagram of the rubber cutting process

Model data testing employed hypothetical data designed to achieve minimum costs based on human resources, robot resources, and human-robot collaboration resources. These resources are detailed in a matrix explained in Tables 1-4. Table 1 explains the activities in the research's precedence diagram, Table 2 explains the model testing matrix, Table 3 details the operational cost settings, and Table 4 explains the supporting cost settings under various conditions.

Table 1. Precedence diagram of the rubber cutting process

Task	Activities
1	Store a storage container at the top of the tree trunk
2	Carry out the cutting process on the upper trunk of the tree
3	Check the quality of the rubber at the top (whether the water volume exceeds what has been determined)
4	Store a storage container at the bottom of the tree trunk
5	Carry out the cutting process at the bottom of the tree trunk
6	Check the quality of the rubber at the bottom (whether the water volume exceeds what has been determined)

Table 2. Model test

Resource	Total Cost (TC)	Information
Man	IDR	Mathematical Model Testing
Robot	IDR	Mathematical Model Testing
Human Robot Collaboration	IDR	Mathematical Model Testing
Human Robot Collaboration	IDR	Mathematical Model Testing "Each row has the same value"
Human Robot Collaboration	IDR	Mathematical Model Testing "Each row has a different value"
Human Robot Collaboration	IDR	Testing Primary Data and Secondary Data

Table 3. Details the operational cost settings for first scenario to fifth scenario

Items	Code	Value
Robot Investment Costs	C_{IR}	100,000,000
Cost of Human Investment	C_{IH}	10,000,000
Robot Operational Costs	C_{OR}	10
Human Operational Costs	C_{OH}	20
Robot Maintenance Costs	C_{MR}	50
Total Number of Tasks	n_T	6
Cost Savings Using Robots	b_2	0
Cost Savings Using Human Robot Collaboration	b_3	0

Table 4. The supporting cost settings under various conditions for first scenario to fifth scenario

Items	Code	Value
Robot Working Hours (Hour Day)	H_{DR}	12
Number of Robot Working Days (Days of Week)	D_{WR}	7
Human Working Hours (Hour Day)	H_{DH}	6
Number of Human Working Days (Days of Week)	D_{WH}	5
Top Rubber Tapping Process Time (Robot)	P_{PAR}	20
Bottom Rubber Tapping Process Time (Robot)	P_{PBR}	20
Tree Navigation Runtime (Robot)	W_{PNR}	20
Top Rubber Tapping Process Time (Human)	P_{PAH}	50
Bottom Rubber Tapping Process Time (Human)	P_{PBH}	50
Tree Navigation Runtime (Human)	W_{PNH}	50

3.1 First Scenario Numerical Testing

The first scenario uses a model with results from decisions to select human resources, where the processing time setting exceeds the cycle time. This was done to test the properties of the model produced without including the cost of robots or human-robot collaboration. The first scenario data is explained in detail in Table 5, with the results of data processing for the first scenario in Table 6, and the results of cost processing for the first scenario data shown in Table 7.

Table 5. First scenario

Task (*i*)	Task-th (*i+1*)	Processing Time		
		Man	Robot	Human Robot Collaboration
1	2,4	10	1500	1500
2	3	20	1500	1500
3	6	20	1500	1500
4	5	10	1500	1500
5	6	20	1500	1500
6	-	15	1500	1500

Table 6. Processing results first scenario

Task (*i*)	*j* tree
1	Human
2	Human
3	Human
4	Human
5	Human
6	Human

Table 7. Cost processing results in the first scenario

Items	Result
Total cost	10,014,000
Number of Workers (Human)	1
Number of Robots	0
Number of Trees processed	1

Calculation of total costs calculated based on the formula equation will produce the same value as the results of the optimization application program. The first scenario test results confirm that the total cost calculated using equation (II.4) matches the results from the optimization application program.

$$\begin{aligned}\text{Total cost} &= (10{,}000{,}000 \times 1) + (100{,}000{,}000 \times 0) + (50 \times 0) + ((20 \times 1 \times 6 \times 3600 \times 5) / (50+50+50)) + \\ &\quad ((10 \times 0 \times 12 \times 3600 \times 7) / (20+20+20)) - 0 - 0 \\ &= 10{,}000{,}000 + 0 + 0 + (2{,}160{,}000 / 150) + 0 - 0 - 0 \\ &= 10{,}000{,}000 + 0 + 0 + (14{,}400) + 0 - 0 - 0 \\ &= 10{,}014{,}000\end{aligned}$$

3.1.1 Analysis of First Scenario Test Results

The analysis aims to remove resources with task times exceeding the 150-unit cycle time (explained in Table 8). Robots and human-robot collaboration options are excluded due to exceeding this limit. With humans selected as the resource, the model analysis yields a total cost of IDR 10,014,400, translating to IDR 1,669,066.07 per task.

Table 8. Eliminate Infeasible Resource Alternatives

Task (*i*)	Task-th (*i+1*)	Processing Time		
		Man	Robot	Human Robot Collaboration
1	2,4	10	0	0
2	3	20	0	0
3	6	20	0	0
4	5	10	0	0
5	6	20	0	0
6	-	15	0	0

3.2. Second Scenario Numerical Testing

The second scenario uses a model with the results of decisions to choose robot resources, where the processing time setting exceeds the cycle time. This was done to test the results of the properties of the model produced without including robot saving costs and human robot collaboration saving costs. The second scenario data is explained in detail in Table 9, with the results of data processing for the second scenario in Table 10, and the results of cost processing for the second scenario data shown in Table 11.

Table 9. Second Scenario

Task (*i*)	Task-th (*i+1*)	Processing Time		
		Man	Robot	Human Robot Collaboration
1	2,4	1500	10	1500
2	3	1500	20	1500
3	6	1500	20	1500
4	5	1500	10	1500
5	6	1500	20	1500
6	-	1500	15	1500

Table 10. Processing Results Second Scenario

Task (*i*)	*j* tree
1	Robot
2	Robot
3	Robot
4	Robot
5	Robot
6	Robot

Table 11. Cost Processing Results in the Second Scenario

Items	Result
Total cost	100,050,450
Number of Workers (Human)	0
Number of Robots	1
Number of Trees processed	1

Calculation of total costs calculated based on the formula equation will produce the same value as the results of the optimization application program.

$$\begin{aligned}\text{Total cost} &= (10{,}000{,}000 \times 0) + (100{,}000{,}000 \times 1) + (50 \times 1) + ((20 \times 0 \times 6 \times 3600 \times 5) / (50+50+50)) + \\ &\quad ((10 \times 1 \times 12 \times 3600 \times 7) / (20+20+20)) - 0 - 0 \\ &= 0 + 100{,}000{,}000 + 50 + (0) + (3{,}024{,}000 / 60) - 0 - 0 \\ &= 10{,}000{,}000 + 100{,}000{,}000 + 50 + (0) + (50{,}400) - 0 - 0 \\ &= 100{,}050{,}450\end{aligned}$$

3.2.1 Analysis of Second Scenario Test Results

Similar to the first scenario, this analysis excluded resources exceeding the 150-unit cycle time (explained in Table 12). In this case, humans and human-robot collaboration are excluded. The model analysis yields a total cost of IDR 100,050,450 with robots selected as the resource, translating to IDR 16,675,000.75 per task.

3.3. Third Scenario Numerical Testing

The third scenario uses a model with the results of the decision to choose human-robot collaboration resources, where the processing time setting exceeds the cycle time. This was done to test the results of the properties of the model produced without including robot saving costs and human robot collaboration saving costs. The third scenario data is explained in detail in Table 13, with the results of processing the third scenario data in Table 14, and the results of cost processing in the third scenario data shown in Table 15.

Table 12. Eliminate Infeasible Resource Alternatives

Task (*i*)	Task-th (*i+1*)	Processing Time		
		Man	Robot	Human Robot Collaboration
1	2,4	0	10	0
2	3	0	20	0
3	6	0	20	0
4	5	0	10	0
5	6	0	20	0
6	-	0	15	0

Table 13. Third Scenario

Task (*i*)	Task-th (*i+1*)	Processing Time		
		Man	Robot	Human Robot Collaboration
1	2,4	1500	1500	10
2	3	1500	1500	20
3	6	1500	1500	20
4	5	1500	1500	10
5	6	1500	1500	20
6	-	1500	1500	15

Table 14. Processing Results Third Scenario

Task (*i*)	*j* tree
1	Human Robot Collaboration
2	Human Robot Collaboration
3	Human Robot Collaboration
4	Human Robot Collaboration
5	Human Robot Collaboration
6	Human Robot Collaboration

Tabel 15. Cost Processing Results in the Third Scenario

Items	Result
Total cost	110,064,850
Number of Workers (Human)	1
Number of Robots	1
Number of Trees processed	1

Calculation of total costs calculated based on the formula equation will produce the same value as the results of the optimization application program.

$$
\begin{aligned}
\text{Total cost} &= (10{,}000{,}000 \times 1) + (100{,}000{,}000 \times 1) + (50 \times 1) + ((20 \times 1 \times 6 \times 3600 \times 5) / (50+50+50)) + ((10 \times 1 \times 12 \times 3600 \times 7) / (20+20+20)) - 0 - 0 \\
&= 10{,}000{,}000 + 100{,}000{,}000 + 50 + (2{,}160{,}000 / 150) + (3{,}024{,}000 / 60) - 0 - 0 \\
&= 10{,}000{,}000 + 100{,}000{,}000 + 50 + (14{,}400) + (50{,}400) - 0 - 0 \\
&= 110{,}064{,}850
\end{aligned}
$$

3.3.1 Analysis of Third Scenario Test Results

This analysis aims to remove resource alternatives with task times exceeding the pre-defined 150-unit cycle time (detailed in Table 16). Specifically, human and robot options are excluded because their processing times surpass the cycle time limit.

The cycle time of human-robot collaboration resources has a cycle time value that is smaller than the cycle time that has been set, while the cycle time of human resources and robot resources has a cycle time value that is greater than the cycle time that has been set. The total cost resulting from the model analysis is IDR 110,064,850 with the selected resource being human-robot collaboration, so that if divided per each task, a value of IDR is obtained 27,516,212.5 per task.

3.4. Fourth Scenario Numerical Testing

The fourth scenario uses a model with the decision to choose the resource that has the fastest cycle time at the lowest cost, where the cycle time value of each column has the same value for each task but has a different cost burden. Testing the fourth scenario does not include the cost of saving robots and the cost of saving human-robot collaboration. This was performed to test the results of the model properties. The fourth scenario data is explained in detail in Table 17, with the results of processing the fourth scenario data in Table 18, and the results of cost processing in the fourth scenario data shown in Table 19. The selected resources are human resources based on optimization applications, because there are differences in values on the value of operational costs, investment costs and maintenance costs. Robot resources have a greater investment value and maintenance costs when compared to human resources. These costs influence the final results of resource selection in each task. Calculation of total costs calculated based on the formula equation will produce the same value as the results of the optimization application program.

Total cost = (10,000,000 × 1)+(100,000,000 × 0)+(50 × 0)+((20 × 1 × 6 × 3600 × 5)/(50+50+50))+((10 × 0 × 12 × 3600 × 7)/(20+20+20)) – 0 – 0
= 10,000,000 + 0 + 0 + (2,160,000 /150) + 0 – 0 – 0
= 10,000,000 + 0 + 0 + (14,400) + 0 – 0 – 0
= 10,014,000

Table 16. Eliminate Infeasible Resource Alternatives

Task (*i*)	Task-th (*i+1*)	Processing Time		
		Man	Robot	Human Robot Collaboration
1	2,4	0	0	10
2	3	0	0	20
3	6	0	0	20
4	5	0	0	10
5	6	0	0	20
6	-	0	0	15

Table 17. Fourth Scenario

Task (*i*)	Task-th (*i+1*)	Processing Time		
		Man	Robot	Human Robot Collaboration
1	2,4	10	10	10
2	3	20	20	20
3	6	20	20	20
4	5	10	10	10
5	6	20	20	20
6	-	15	15	15

Table 18. Processing Results Fourth Scenario

Task (*i*)	*j* tree
1	Human
2	Human
3	Human
4	Human
5	Human
6	Human

Table 19. Cost Processing Results in the Fourth Scenario

Items	Result
Total cost	10,014,000
Number of Workers (Human)	1
Number of Robots	0
Number of Trees processed	1

3.5. Fifth Scenario Numerical Testing

The fifth scenario uses a model with the decision to choose the resource that has the fastest cycle time at the lowest cost, where the cycle time value of each column has a different value for each task. Testing the fifth scenario does not include the cost of saving robots and the cost of saving human-robot collaboration. This was carried out to test the results of the model properties. The fifth scenario data is explained in detail in Table 20, with the results of the fifth scenario data processing in Table 21, and the cost processing results of the fifth scenario data shown in Table 22.

The results of data processing for the fifth scenario produce robot resources in the first task, human robot collaboration resources in the second task, human resources in the third and fourth tasks, human robot collaboration resources in the fifth task and robot resources in the sixth task. The results of processing the optimization application for each task select the fastest cycle time for each resource.
Calculation of total costs calculated based on the formula equation will produce the same value as the results of the optimization application program.

Total cost = (10,000,000 × 1)+(100,000,000 × 1)+(50 × 1)+((20 × 1 × 6 × 3600 × 5)/(50+50+50))+((10 × 1 × 12 × 3600 × 7) / (20+20+20)) – 0 – 0
= 10,000,000+100,000,000+50+(2,160,000 /150) + (3,024,000 / 60) – 0 – 0
= 10,000,000 + 100,000,000 + 50 + (14,400) + (50,400) – 0 – 0
= 110,064,850

Table 20. Fifth Scenario

Task (*i*)	Task-th (*i+1*)	Processing Time		
		Man	Robot	Human Robot Collaboration
1	2,4	1500	10	280
2	3	1500	280	20
3	6	20	270	1500
4	5	10	1500	250
5	6	270	1500	20
6	-	260	15	1500

Table 21. Processing Results Fifth Scenario

Task (*i*)	*j* tree
1	Robot
2	Human Robot Collaboration
3	Human Robot Collaboration
4	Human
5	Human
6	Robot

Table 22. Cost Processing Results in the Fifth Scenario

Items	Result
Total cost	110,064,850
Number of Workers (Human)	1
Number of Robots	1
Number of Trees processed	1

3.5.1 Analysis of Fifth Scenario Test Results

This analysis aims to remove resource alternatives with task times exceeding the pre-defined 150-unit cycle time (detailed in Table 23). The total cost resulting from implementing the fifth test data algorithm is IDR110.064.850 by completing tasks on 2-task human resources, 2-task robot resources, and 2-task human-robot collaboration resources. If calculated based on the calculation reference for each resource, then 2 × IDR1,669,066.07 = IDR3.338.132.14 for human resources, 2 × IDR16,675,075 = Rp33,350,150 for robot resources, then 2 × IDR27,516,212.5 = IDR 55,032,425 for human robot collaboration resources with a total cost of IDR91,720,707.14.

Table 23. Eliminate Infeasible Resource Alternatives

Task (*i*)	Task-th (*i+1*)	Processing Time		
		Man	Robot	Human Robot Collaboration
1	2,4	0	10	0
2	3	0	0	20
3	6	20	0	0
4	5	10	0	0
5	6	0	0	20
6	-	0	15	0

Table 24. Optimization Application Data Results and Mathematical Models

Scenario	Optimization Application Program Results (IDR)	Manual Calculation Results (IDR)	Information
1	10,014,400	10,014,400	Each human resource has a cost of IDR 1,669,066.07
2	100,050,450	100,050,450	Each robot resource has a cost of IDR 16,675,075
3	110,064,850	110,064,850	Each human-robot collaboration resource costs IDR 27,516,212.5
5	110,064,850	91,720,707.14	a. The first alternative is human resources with the addition of 11 tasks (addition of 2 trees). b. The second alternative is robot resources with the addition of 1 tasks (addition of 1 tree). c. The third alternative is human-robot collaboration resources with the addition of 1 tasks (addition of 1 tree).

According to Table 24, Scenario 5, subtracting the results of the Optimization Application Program from the Manual Calculation Results yields a difference of IDR18,344,142.86. This scenario represents the lowest overall cost option.

The resulting difference value which is then developed and distributed if using alternative human resources, will produce IDR18,344,142.86 divided by IDR1,669,066.07 = 10.99 ≈ 11 tasks. If each tree has 6 tasks, then 11 divided by 6 will produce 2 additional trees carried out by human resources. If use alternative robot resources, you will generate IDR18,344,142.86 divided by IDR16,675,075 = 1.1 ≈ 1 tasks. If each tree has 6 tasks, then 1 divided by 6 will produce 0.17 trees or 1 additional tasks in the next tree which are performed by robot resources. If use alternative human-robot collaboration resources, you will generate IDR18,344,142.86 divided by IDR 27,516,212.5 = 0.67 tasks. If each tree has 6 tasks, then 0.67 divided by 6 will produce 0.11 trees or 1 additional tasks in the next tree which are carried out by human-robot collaboration resources.

3.5.2 Analysis of Overall Scenario Test Results

Analysis of the first, second, third and fifth test data is to eliminate resource alternatives that have task times exceeding the cycle time, This analysis aims to remove resource alternatives with task times exceeding the pre-defined 150-unit cycle time. The results of the analysis on the first, second, third and fifth test data were then compared with the results of the optimization application which are explained in detail in Table 24 and comparison between method of DCA and non-DCA in Table 25.

The total workforce is based on secondary data (Komala, 2017), and the total calculation of the number of trees carried out by the rubber sap cutting process is based on primary data (Irfan, 2022), so there are calculations including:

a. Labor costs are Rp76,000 per day
b. The total work done in 1 week is 6 times
c. Total working hours per day 4 hours 30 minutes (16,200 seconds)
d. The number of trees that undergo the cutting process is 500 trees per day
e. Total yield of rubber latex per day is 200 kg (200,000 grams)

If the calculation is carried out in weeks based on the objective function formula, we will get:

a. Labor costs per week Rp76.000 × 6 = Rp456,000
b. Total working hours per week 4.5 × 6 = 27 Hours (97,200 seconds)
c. Number of trees per week 500 × 6 = 3,000 trees
d. Labor costs per tree: Rp456,000 / 3,000 = Rp152 / tree trunk
e. Rubber cutting process time + Navigation to each tree: 97,200 / 3,000 = 32.4 seconds / tree trunk
f. Rubber latex yield per week is 200,000 × 6 = 1,200,000 grams
g. The yield of rubber sap per trunk is 1,200,000 / 3,000 = 400 grams / stick

Comparison of total cost calculations between alternative double cut process research (DCA) and alternative non double cut process research (Non-DCA) which is explained in detail in Table 30. Table 30 contains items for the number of trees that can be tapped per week (unit of trunk), is 273,500 trees, so that per day the tapping process can be performed as many as 273,500 / 6 = 45,583.333 ≈ 45,583 trees per day, and if the average is 1 hectare (Ha) of rubber trees consists of 400 trees, so by using the concept of human collaborative resources, robots can carry out the process of tapping rubber sap with a plantation area of 45,583 / 400 = 113.95 hectares (Ha) ≈ 114 hectares (Ha) every day. The calculation of profit in Table 25 that is carried out is a calculation of total income minus total labor costs, not yet deducting other costs because other costs are not included in the calculation or mathematical model that has been developed, so the point regarding profit per month has not been calculated correctly maximum.

Table 25. Comparison of DCA and Non-DCA Processes

Items	Code	*Non-DCA*	*DCA*
Robot Working Hours (Hour Day)	H_{DR}	0	12
Number of Working Days (Days of Week) Robot	D_{WR}	0	7
Human Working Hours (Hour Day)	H_{DH}	4.5	6
Number of Human Working Days (Days of Week)	D_{WH}	6	5
Top Rubber Tapping Process Time (Robot)	P_{PAR}	0	13
Bottom Rubber Tapping Process Time (Robot) + Tree Navigation Process Time (Robot)	$P_{PBR}+ W_{PNR}$	0	19.67
Top Rubber Tapping Process Time (Human)	P_{PAH}	0	17.07
Bottom Rubber Tapping Process Time (Human) + Tree Navigation Process Time (Human)	$P_{PBH}+ W_{PNH}$	32.4	47.07
Number of trees that can be tapped per week (stems)		3,000	273,500
Rubber sap per tree trunk that can be produced (grams per week)		400	400
Rubber sap per tree trunk that can be produced (grams per week) in the upper and lower DCA processes		400	800
Total rubber latex produced per week (grams)		1,200,000	218,800,000

Total rubber latex produced per week (Kg)		1,200	218,800
Rubber Selling Price (IDR/Kg)		7,000	7,000
Income per week (IDR)		8,400,000	1,531,600,000
Income per month (IDR)		33,600,000	6,126,400,000
Total Costs (expenses) (IDR / month)		1,824,000	1,618,234,564.595
Profit per month (IDR)		31,776,000	4,508,165,435.405

3.6. Sixth Scenario Numerical Testing

The sixth scenario uses a model with the results of the decision to choose the resource that has the fastest cycle time at the lowest cost. The data used in the sixth scenario uses primary data and secondary data for each task. Testing the sixth scenario included robot saving costs and human robot collaboration saving costs. This was carried out to get results that were close to the actual data.

Table 26 shows the value of costs, number of tasks, cost savings calculated based on primary data and secondary data, while Table 27 shows the values of process time, human work time, robot work time, human navigation time, robot navigation time, rubber latex tapping process time based on primary data and secondary data. Labor investment costs are costs based on estimates of developing worker resources (training) and so on, while savings costs using robot resources, costs using human robot collaboration resource savings, and operational costs are based on local regional salary values (Susanto, 2019).

Robot investment costs are calculated based on search values in the marketplace as a price reference, while robot operational costs are based on the KWH value used when the robot operates on plantations. The following is a breakdown of the costs of human resources, robot resources and human-robot collaboration resources, including:

1. Labor resource investment costs (training and recruitment) are IDR15,000,000, - (Susanto, 2019)
2. Robot resource investment costs based on the marketplace are $105,000 with details of $35,000 for Robot investment costs, $35,000 for unexpected costs, while $35,000 for shipping costs, taxes, etc. ($105,000 × Rp15,840 =IDR1,663,200,000 (Exchange rate 1 Dollar = Rp15,840, April 9 2024)
3. Operational costs for human resources, data collection was carried out based on the UMR for the Purwakarta area, which is IDR4,499,768 (date 09 April 2024)
   a. 1 month : average 22 working days
   b. 1 day : on average working 8 hours (effectively working 6 hours per day)
   c. 1 month : 22×6×3600 = 475,200 sec.
   d. Rp4,499,768 / 475,200 = Rp9.5/sec.
4. Operational costs of robot resources, data calculations are carried out based on the KWH value with the assumption that the robot power is 3.6 KWH (Susanto, 2019). This data is calculated based on the value/second calculation, with the rupiah value per KWH being IDR1,699.53 / KWH (assumed power 3500 – 5000 watts household industrial scale, 03 February 2024)
   a. 3.6 KWH x Rp1,699.53 per KWH = IDR6,118.308 per hour
   b. 1 hour = 3600 sec.
   c. Operational costs per second include:
   d. Rp 6,118.308 / 3600 = IDR1.69953 ≈ Rp2 per sec.
5. Secondary data on Maintenance Costs of EUR 11.7/h (Mahdi et al, 2023)
   a. 1 EUR = Rp.17,211.74 (dated April 09, 2024)
   b. (EUR11.7 × Rp17,211.74) / 3600 = Rp55.94 per sec.
6. Tapping process (both top and lower area) with human labor is 17.07 seconds per tap.
7. The navigation process to each tree, with human resources, is 30 second.
8. Tapping process (both top and lower area) with robot resources is 13.00 second per tap.
9. The navigation process to each tree, with robot resources, is 6.67 second.
10. Cost savings using robot resources is IDR10,000,000.
11. Cost savings using human-robot collaboration resources is IDR20,000,000.
12. Effective robot working a day is 12 hours.
13. Effective robot working a week is 7 days.
16. Effective human working a day is 6 Hours.
17. Effective human working a week is 5 days.

The sixth scenario data is explained in detail in Table 28 with the results of data processing for the sixth scenario in Table 29, and the results of cost processing for the sixth scenario data shown in Table 30. The results of data processing for the sixth scenario produce robot resources in the first task, human robot collaboration resources in the second task, human resources in the third and fourth tasks, human robot collaboration resources in the fifth task and robot resources in the sixth task. The results of processing the optimization application for each task select the fastest cycle time for each resource.

Table 26. Sixth Scenario Operational Cost Settings

Items	Code	Value
Robot Investment Costs	C_{IR}	1,663,200,000
Cost of Human Investment	C_{IH}	15,000,000
Robot Operational Costs	C_{OR}	2
Human Operational Costs	C_{OH}	9.5
Robot Maintenance Costs	C_{MR}	55.94
Total Number of Tasks	n_T	6
Cost Savings Using Robots	b_2	10,000,000
Cost Savings Using Human Robot Collaboration	b_3	20,000,000

Table 27. Sixth Scenario Operational Cost Settings

Items	Code	Value
Robot Working Hours (Hour Day)	H_{DR}	12
Number of Robot Working Days (Days of Week)	D_{WR}	7
Human Working Hours (Hour Day)	H_{DH}	6
Number of Human Working Days (Days of Week)	D_{WH}	5
Top Rubber Tapping Process Time (Robot)	P_{PAR}	13
Bottom Rubber Tapping Process Time (Robot)	P_{PBR}	13
Tree Navigation Runtime (Robot)	W_{PNR}	6.67
Top Rubber Tapping Process Time (Human)	P_{PAH}	17.07
Bottom Rubber Tapping Process Time (Human)	P_{PBH}	17.07
Tree Navigation Runtime (Human)	W_{PNH}	30

Table 28. Sixth Scenario

Task (i)	Task-th ($i+1$)	Processing Time		
		Man	Robot	Human Robot Collaboration
1	2,4	1500	10	280
2	3	1500	280	20
3	6	20	270	1500
4	5	10	1500	250
5	6	270	1500	20
6	-	260	15	1500

Table 29. Processing Results Sixth Scenario

Task (i)	j tree
1	Robot
2	Human Robot Collaboration
3	Human Robot Collaboration
4	Human
5	Human
6	Robot

Table 30. Cost Processing Results

Items	Result
Total cost	1,618,234,564,595
Number of Workers (Human)	1
Number of Robots	1
Number of Trees processed	1

Calculation of total costs calculated based on the formula equation will produce the same value as the results of the optimization application program.

Total cost = (15,000,000×1)+(1,663,200,000×1)+(55.94×1)+((9.5×1×6×3600×5)/(17.07+17.07+30))+((2×1×12×3600×7)/(13+13+6.67))–(2×10,000,000)–(2×20,000,000)
=15,000,000+1,663,200,000+55.94+(1,026,000 / 64.14)+(302.4 / 32.67) – 20,000,000 – 40,000,000

=15,000,000+1,663,200,000+55.94+ (15,996.26) +(9,26)–20,000,000–40,000,000
= 1,618,234,564,595

3.6.1 Analysis of Test Results for the Sixth Scenario

The analysis of the sixth test data is that the total costs generated by implementing the sixth test data algorithm are IDR1,618,234,564,595 with different resources for each task. Human resources get 2 tasks (third and fourth tasks), robot resources 2 tasks (first task and sixth task), and human robot collaboration resources 2 tasks (second task and fifth task).

3.6.2 Comparative Analysis of the Sixth Scenario with Current Conditions (DCA and Non-DCA)

The sixth scenario is an alternative double cut (DCA) process, namely the process of cutting rubber latex on the top and bottom of the rubber tree which is performed at the same time, while the current condition is that the operator is carrying out a non-DCA (alternative double cut) process, namely the cutting process only the top part or only the bottom part is done.

CONCLUSION

The developed model for minimizing costs in rubber latex cutting identifies three optimal resource options: 1. The model that has been developed to produce minimal costs in the rubber (latex) cutting process in rubber plantations has three alternative resources, namely human resources, resources robot power, and human-robot collaboration resources. The allocation of the three resource alternatives has different tasks, namely the first task is carried out by robots, the second task is carried out by human-robot collaboration, the third task is carried out by humans, the fourth task is carried out by humans, the fifth task is carried out by human-robot collaboration, and the sixth task is carried out by robot. The model that has been developed to produce minimum costs has main constraints that need to be considered, including investment costs, operational costs, and maintenance costs. 2. The model that has been developed to produce minimum costs, has indications that:

a. If robot resources are not yet available, then the choice of resources to produce minimum costs in the rubber (latex) cutting process is human resources, because human resources produce the minimum costs which are influenced by investment costs and operational costs which are small in value and the absence of maintenance costs.
b. The model developed can allocate three alternative resources. The allocation of resource selection depends on parameters including investment costs, operational costs, maintenance costs, cost savings using robots, cost savings using human-robot collaboration, working hours per day, number of working days per week, navigation process time, rubber cutting process time rubber.
c. The optimization application program using primary data and secondary data in the sixth scenario produces a minimum total cost of IDR1,618,234,564,595.

Suggestions for further research in developing the model from this research are:

1. The development of the model in this research uses the concept of Technology Readiness Level (TRL), to see the readiness to apply technology in plantations, especially in Rubber Plantations.
2. Develop a model for rubber plantations to get a model that is more complex and closer to the actual concept. This is necessary because real-world rubber plantations often involve planting coffee or other crops between the rubber tree trunks.

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