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THE OPTIMAL REPLACEMENT TIME FOR HARVESTERS: AN ECONOMIC ANALYSIS

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ABSTRACT

This research sought to identify the ideal timeframe for replacing a Harvester, used in forest harvesting, employing a comparative evaluation of different economic methods. A John Deere 1270D harvester, equipped with a 270-model head was utilized in this study. The machine's cost per hour worked was calculated by adding fixed costs with variable costs. The methods used to determine the machine's optimal replacement time were: the Total Average Cost (TAC) and the Equivalent Annual Cost (EAC), which consider discrete functions, and the Terminal Cycle and Constant Chain Replacement, which consider continuous functions. The four methods differed in their indication of the optimal replacement time for the harvester. Although the TAC is a simple and well-known method, it did not yield an adequate result (2 years). This is because replacing a forest machine usually occurs over a longer period of use, with current preventive and predictive maintenance routines. This discrepancy arises from the high acquisition and operational costs, as well as the method's failure to account for the variation of capital over time (interest rate) and the revenues or production of the harvester, which significantly affects the analysis. Utilizing the discount rate, the EAC proved to be more efficient than the TAC, yielding a result that is more aligned with the reality of the forest sector (6 years). Furthermore, it is the most widespread method in machine and equipment replacement studies due to its simplicity, ease of application, and efficiency. The Chain Replacement method provided an optimal replacement time between 7 and 8 years, also consistent with the reality of companies in the forest sector engaged in forest harvesting for an extended period. Therefore, this method can be considered in decision-making as it takes into account the cost and revenue variables of the machine. Determining the useful life of a machine used in forest harvesting from an economic perspective, or the period in which it performs its activities with the lowest operational cost, is directly related to its lowest production cost. In the present study, the most suitable methods to determine the optimal replacement time for the harvester were the EAC and the Chain Replacement method.

Keywords: Forest Harvesting; Harvesting Costs; Operational Development.

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DETERMINAÇÃO DO MOMENTO ÓTIMO DE SUBSTITUIÇÃO DE UM HARVESTER: UMA ABORDAGEM ECONÔMICA

RESUMO – O objetivo deste trabalho foi identificar o momento ótimo para substituição de um Harvester utilizado na colheita florestal, comparando diferentes métodos econômicos. A máquina florestal utilizada foi o Harvester John Deere modelo 1270D, com cabeçote modelo 270. O custo da máquina por hora trabalhada foi calculado pela soma dos custos fixos com os custos variáveis. Os métodos utilizados para determinação da substituição ótima da máquina foram o Custo Médio Total (CMT) e o Custo Anual Equivalente (CAE), que consideram funções discretas e o Ciclo Terminal e Cadeia de Substituição Constante, que consideram funções contínuas. Os quatro métodos utilizados diferiram entre si na indicação do momento ótimo de substituição do Harvester. O CMT, apesar de ser um método simples e conhecido, não conduziu a um resultado adequado (2 anos), pois, a substituição de uma máquina florestal é usualmente feita com um período maior de uso, com as atuais rotinas de manutenção preventivas e preditivas. Tal divergência é justificada devido aos elevados valores de aquisição e de custo operacional, além do método não considerar a variação do capital no tempo (a taxa de juros) e as receitas ou a produção do Harvester, o que impacta drasticamente a análise. O CAE, por utilizar a taxa de desconto, foi mais eficiente que o CMT e forneceu um resultado mais coerente com a realidade do setor florestal, sendo 6 anos. Além disso, é o método mais difundido nos estudos de substituição de máquinas e equipamentos, por ser simples, de fácil aplicação e eficiente. Já o método da Cadeia de Substituição forneceu um momento ótimo de substituição entre 7 e 8 anos, também coerente com a realidade das empresas do setor florestal que praticam a atividade de colheita florestal por um longo período. Portanto, este método pode ser considerado na tomada de decisão, por considerar as variáveis de custo e receita da máquina. A determinação da vida útil de uma máquina utilizada na colheita florestal, do ponto de vista econômico, ou o período em que ela executa suas atividades com menor custo operacional está diretamente relacionada com seu menor custo de produção, e no presente estudo, os métodos mais adequados para determinar o momento ótimo de substituição do Harvester foram o CAE e o método da Cadeia de Substituição.

Palavras-Chave: Colheita florestal; Custos de colheita florestal; Desenvolvimento operacional.

1. INTRODUCTION

The implementation of novel techniques to increase productivity in forest harvesting has prompted substantial investments in machinery and equipment, resulting in high acquisition and operational costs. Hence, assessments integrating technical, economic, and environmental parameters are imperative to enhance energy efficiency and mitigate fixed costs (Santos et al., 2020).

To attain the anticipated outcomes in productivity and mechanical uptime of these machines, repair and maintenance expenses have risen due to wear and tear (Simões et al., 2014). Nonetheless, the wear resulting from operational time and activities can be mitigated through effective maintenance protocols, thereby prolonging the machines' lifespan (Linhares et al., 2012).

However, various factors, including advancements in technology, evolving service demands and machine capabilities, modifications in tax laws, and unforeseen circumstances, substantiate the replacement of machines with more advanced ones. Such upgrades often lead to decreased operational expenses and enhanced efficiency (Marques et al., 2005). Additionally, environmental and social concerns should be taken into account, as prolonged machine usage tends to result in higher fuel consumption, increased greenhouse gas emissions, and elevated accident risks, among other implications (Zhang et al., 2016), impacting the company's natural capital.

The decision to replace machinery or equipment is a multifaceted process requiring careful consideration. It necessitates a comprehensive understanding and definition of various parameters, including the planning horizon, operational expenses, maintenance and repair protocols, asset depreciation, interest rates, and economic criteria (Cesca, 2018; Schweier et al., 2019).

Determining whether to replace a machine entails evaluating different project alternatives, where one option involves retaining existing machinery while the other entails acquiring new ones, examined through a financial lens (Silva et al., 2015). Delayed or premature replacements can result in financial setbacks, either through capital recovery or elevated operational costs, respectively.

Machines that are decommissioned are typically replaced when they reach a state of operational incapacity, characterized by wear that progressively impairs their efficiency, resulting in decreased productivity and service quality (Hejazian et al., 2019). However, not all machine retirements entail complete cessation of use; a machine discarded by one company may undergo repurposing for alternative activities within the same organization before eventual replacement or sale to another entity (Miyajima et al., 2020).

Factors such as the machine's lifespan and residual value are taken into account when determining the optimal replacement period (Simões et al., 2010). The decision-making process regarding replacement presupposes that the planning horizon, future investments, and operational expenses have been predetermined and thoroughly evaluated (Diniz et al., 2019).

The prevalent methods utilized in determining the optimal replacement time for machines involve the consideration of both discrete and continuous functions. Discrete functions pertain to either a finite or infinite set of values, while continuous functions encompass a non-enumerable set of values. Under discrete functions, the primary economic criteria include the Total Average Cost (TAC) and the Equivalent Annual Cost (EAC). Conversely, continuous functions entail the terminal cycle, partial or phased replacement, and the replacement chain (Valverde and Rezende, 1997).

In Brazil, the primary system used in the pulp industry is the cut-to-length method, where the tree is processed at the forest harvesting site by the harvester and extracted to the roadside by the forwarder (Sena et al., 2023). The productivity of the machines involved in forest harvesting is crucial for the operation, and to achieve good indicators, the machine must show adequate mechanical availability, indicating its reliability (Schettino et al., 2022).

The harvester, an integral component of forest mechanization, is a self-propelled vehicle equipped with low-pressure, high-flotation tires (LPHF), metallic or hybrid tracks (tires with tracks), and a hydraulic boom designed to access trees. Teamed with the head, the harvester undertakes a range of tasks including felling, delimbing, debarking, bucking, and stacking of wood (Zhang et al., 2022). The widespread adoption of harvesters has bolstered productivity, enhanced workplace safety, and trimmed operational expenses, rendering these machines a competitive choice and a staple in forest harvesting operations across Brazil (Santos et al., 2022).

Given the pivotal role of the harvester in mechanized forest harvesting, investigations into determining the optimal replacement time are vital for optimizing operational efficiency and fostering the advancement of the forestry sector. Consequently, this study seeks to delineate the ideal replacement period for a harvester by comparing different economic calculation methods, elucidating their respective applicability across different scenarios.

2. MATERIAL AND METHODS

2.1 Characterization of the evaluated machine

The forest machine evaluated was the John Deere 1270D harvester, equipped with a John Deere 6081 engine boasting a nominal power of 215 hp (160 kW), and featuring hydrostatic transmission. It had an attached John Deere 270 head, capable of cutting diameters ranging from 4 to 62 cm. The machine was equipped with LPHF tires on three drive axles, and metallic tracks connecting the front pairs of wheels. The rear tires were ballasted with 50% water. The chassis is articulated to facilitate maneuvers, and all mechanisms are operated by the operator in the cabin using a joystick and buttons on the control panel. The cabin is leveled at an angle of 21° for both uphill and downhill inclines (Leite, 2012).

The study considered the entire operational lifespan of the machine. The acquisition cost of the machine, along with its associated expenses in US dollars (USD), were adjusted using an exchange rate of US\$1.00 = R\$5.00 to accurately reflect the prevailing economic conditions. The operational costs and data required for analyzing the optimal replacement time were computed using the following parameters (Table 1):

Table 1. Data used for determining the operational cost of the Harvester

Tabela 1. Dados utilizados para determinação do custo operacional do Harvester

Items	Values
Va = acquisition value of the machine (US$)	772,573.53
Vr = resale value, 10% Va (US$)	77,257.35
N = economic life (years)	10
H = hours worked per year (h year^{-1})	5,889.60
h = hours worked per day (h day^{-1})	24
D = days worked per year (d year^{-1})	312
E.O = operational efficiency (%)	80
he = effective annual usage hours (h year^{-1})	4,711.68
dm = days worked per month (d month^{-1})	26
i = annual interest rate (% p.a.)	8
S = insurance (% p.a.)	0.02
Pu = fuel price (US$ L^{-1})	1.28
c = fuel consumption per effective hour (L h^{-1})	16
ILG = lubricant and grease cost index (%)	20
I = hydraulic oil consumption index (%)	20
P = tire price (US$ unit^{-1})	3,520.59
Hpe = tire lifespan in effective hours (h/unit)	12,500
Ne = number of tires	6
Sop = monthly salary of operators (US$ month^{-1})	508.53
No = number of operators per machine	3
ES = social charges rate (% of salary)	1.74
Des = social expenses (US$/month)	376.31
CTP = personnel transportation cost (US$/he)	0.41
CTM = machinery transportation cost (US$/he)	0.31
CAD = operation administration cost (US$/he)	0.22

Adapted from Leite, 2012
Adaptado de Leite, 2012

2.2 Calculation of the total hourly cost of the Harvester

The total hourly cost of the Harvester was determined by adding both fixed and variable costs (Leite et al., 2014). Fixed costs comprise all expenses unaffected by the machine's operational hours and are calculated using the following equation:

$$CF = D + JS + A + T \qquad \text{(Eq. 1)}$$

Where: D = exponential depreciation; JS = interest, insurance, and taxes; A = shelter; T = administrative fees.

Variable costs are those incurred when the machine is in operation, calculated per effective working hour, determined by the equation:

$$CV = C + Gl + Oh + Pe + MR + MO + TP + TM \qquad \text{(Eq. 2)}$$

Where: C = fuel costs; Gl = lubricant costs; Oh = hydraulic oil costs; Pe = tire costs; MR = maintenance and repair costs; MO = labor costs; TP = personnel transport costs; TM = machinery transport costs.

2.3 Total Average Cost (TAC) method

The Total Average Cost (TAC) method for determining the optimal replacement time does not incorporate capital adjustment through an interest rate. Operational and maintenance costs are tallied at the conclusion of each period. Replacement is deemed optimal when the total average cost is minimized over the analyzed periods, signifying the period with the lowest TAC as the replacement interval (Valverde and Rezende, 1997).

2.4 Equivalent Annual Cost (EAC)

The Equivalent Annual Cost (EAC) is the uniform annual cost the machine incurs during its useful life, equivalent to the present value of the cash flow, considering all costs throughout its productive life. It is obtained by multiplying the present value of all costs over "n" periods by the capital recovery factor, based on a given interest rate (Silva, 2005; Rezende and Oliveira, 2013; Santos et al., 2016a).

$$VA = Va - V_r / (1+i)^n + \sum(O_n + M_n)/1+i)^{ni} \qquad \text{(Eq. 3)}$$

Where: Va = present value of the machine's costs after n periods of use; Va = investment or acquisition cost of the machine; Vr = residual value at the end of the n-th period, calculated at instant n+1; On = operational cost; Mn = maintenance cost; i = interest rate; n = periods of use of the harvester (in years).

The EAC can be calculated according to the following equation:

$$CAE = (VA * i) / [1 – (1 + i)^{-n}] \qquad \text{(Eq. 4)}$$

Where: EAC = Equivalent Annual Cost; VA = present value of the machine's costs after n periods of use; i = interest rate; n = periods of use of the harvester (in years).

The period in which the EAC is minimized, considering an analysis horizon of one to ten years, corresponds to the economic life of the asset and, therefore, the optimal time to replace it.

2.5 Continuous functions or differential equations

This method operates under the assumption that the costs and revenues attributed to the harvester follow continuous functions. The profit function is formulated by defining continuous functions for all revenues and costs generated over the machine's economic lifespan. The optimization of the total profit equation entails computing the derivative with respect to the decision variable and determining the variable value that maximizes total profit (Marques et al., 2005).

2.6 Terminal cycle

In the terminal cycle approach, a company acquires a machine and limits its planning horizon to the time the asset will remains operational. This period ends when the machine wears out, reaching the end of its economic useful life, and is then retired, representing a single terminal cycle.

Let B(t) be the discounted profit of the machine, assuming it is already in service from the start until the moment of its replacement at an unknown instant T. Q(t) denotes the gross income generated by the machine within the time interval (t = t+dt), defined as the difference between operational costs and production value, excluding the initial investment depreciation cost (C). S(T) is the resale value of the machine at instant T; i is the continuous interest rate. As described by Masse (1962):

$$B(t) = {}_0\int^t Q(t)e^{-i(t)} * \delta t+S(T)\ e\text{^}(-i(T))-C \qquad \text{(Eq. 5)}$$

Where: B(t) = discounted profit of the machine; Q(t) = gross income generated by the machine; S(T) = resale value of the machine; C = investment cost (or acquisition value); i = continuous interest rate; t = time period (in years).

Q(t) represents the effect of wear and obsolescence, varying inversely with T, while S(T) is a function of T, which becomes relatively small when T reaches a certain value. The optimal service time is obtained by finding the maximum profit point, i.e., deriving the B(T) function concerning T and setting the first derivative to zero (Equation 6). For this to be a maximum point, the second derivative must be less than zero (Equation 8).

$$dB/dt = 0 = [Q(T)-i(T)S(T) + S'(T)]e^{-i(T)} \qquad \text{(Eq. 6)}$$

$$Q(T) = i(T)S(T) - S'(T) \qquad \text{(Eq. 7)}$$

$$d^2B/dT^2 < 0 \qquad \text{(Eq. 8)}$$

$$Q = iS - S' \qquad \text{(Eq. 9)}$$

$$iS = Q + S' \qquad \text{(Eq. 10)}$$

Equation 10 indicates that upon reaching the end of the service life T, the interest on the residual value equals the profit plus the loss of residual value. Consequently, at the optimal replacement time, the marginal revenue equals the marginal opportunity cost (Valverde and Rezende, 1997). Notably, it is crucial to emphasize that the initial cost of acquiring the machine was eliminated in the differentiation process, implying that its initial cost does not impact the determination of the optimal replacement time.

2.7 Indefinite and constant replacement chain

The replacement chain process involves retiring the old machine followed by the introduction of a new one, successively. Thus, a new machine will be replaced by a second one, the second by a third, creating a chain of several cycles that repeat indefinitely.

The first condition is the terminal convention, where at some point, the chain eventually stops, and the last machine is retired. The second condition is to establish an optimal time to replace the machine, repeating the operation indefinitely. According to Masse (1962):

$$B(\Theta) = \int Q(t)e^{-i(t)}*dt+S(\Theta)e^{-i(\Theta)}-C \qquad \text{(Eq. 11)}$$

Where: $B(\Theta)$ = discounted profit of the machine; $Q(t)$ = gross income generated by the machine; $S(\Theta)$ = resale value of the machine; = investment cost (or acquisition value); i = continuous interest rate; t = time unit (year).

The total discounted profit of the chain is constant. Therefore:

$$B = [1/1-e^{-i\Theta}]*B_{\Theta} \qquad \text{(Eq. 12)}$$

Where: $B = B_{\Theta}+Be^{-i\Theta}$, which is the present value of an annual perpetual series of B received each year (t), or

$$B(\Theta) = [1/(1-e^{-i(\Theta)})] * \int Q(t)e^{-i(t)}*dt + S(\Theta)e^{-i(\Theta)} - C \qquad \text{(Eq. 13)}$$

The optimal service duration is the value of Θ that reduces $dB/d\Theta = 0$, satisfying the following equation:

$$iB(\Theta) = Q(\Theta) - iS(\Theta) + S'(\Theta) \qquad \text{(Eq. 14)}$$

Assuming the residual value and its derivatives are negligible:

$$iB(\Theta) = Q(\Theta) \qquad \text{(Eq. 15)}$$

Equation 15 indicates that in the optimal period Θ, the interest on the discounted profit value of the chain equals the gross income of the old machine at the present moment, i.e., the company maximizes the present value of the entire receipt flow of a chain more than the flow associated with the first machine.

The difference between the criteria expressed by equations (14) and (7) reflects the opportunity cost of delaying the receipts from the next and subsequent machines. The higher these receipts, the quicker the company will replace the current machine.

3. RESULTS

3.1 Operational Cost of the Harvester

The operational cost of the John Deere 1270D harvester amounted to US$103.09 per hectare. This calculation factored in a real interest rate of 8% per annum, an operational efficiency of 80%, and a work schedule spanning three shifts of 8 hours each. The exchange rate applied was US$1.00 = R$5.00. Notably, the operational cost was primarily composed of three key components: maintenance and repairs (39.74%), fuel (20.53%), and depreciation (14.76%). Cumulatively, these three elements constituted 75.03% of the total operational cost (Table 2).

3.2 Total Average Cost (TAC) method

Residual values, as well as investment and operational costs, were used to calculate the TAC. The minimum TAC occurred in the second year, with a value of US$459,934.63, which is the recommended period for machine replacement according to this method (Table 3).

3.3 Equivalent Annual Cost (EAC) Method

The optimal replacement time for the harvester using the EAC method is at 6 years, as this period shows the lowest equivalent annual cost, amounting to US$443,791.51 (Table 3).

3.4 Terminal Cycle Method

According to the Terminal Cycle method, the optimal time to retire the harvester and cease activities occurs when its marginal cost

Table 2. Operational cost components of the John Deere Harvester Model 1270D, in dollars per effective working hour (US$ he^{-1}) and percentage (%)

Tabela 2. Componentes do custo operacional do Harvester John Deere, modelo 1270D, em dólares por hora efetiva trabalhada (US$ he^{-1}) e porcentagem (%)

Operational cost components of the Harvester	Value (US$ he^{-1})	Percentage (%)
Labor	6.76	6.56%
Personnel Transportation	0.41	0.40%
Machinery Transportation	0.31	0.30%
Depreciation	14.76	14.32%
Interest, Taxes, and Insurance	7.80	7.57%
Shelter	1.23	1.19%
Administrative Fees	1.64	1.59%
Fuel	20.53	19.91%
Lubricants	4.11	3.98%
Hydraulic Oil	4.11	3.98%
Tire Cost	1.69	1.64%
Maintenance and Repairs	39.74	38.56%
Total	103.09	100%

Adapted from Leite, 2012 and Leite et al, 2014
Adaptado de Leite, 2012 e Leite et al, 2014

Table 3. Variables used for calculating the optimal replacement time of the John Deere Harvester, model 1270D, with values in US$1,000.00. VR = Residual Value; CI = Investment Cost; CO = Operational Cost; COA = Cumulative Operational Cost; CTM = Average Total Cost; CIA = Current Investment Cost; COA = Current Operational Cost; COAA = Cumulative Current Operational Cost; CTA = Current Total Cost; EAC = Equivalent Annual Cost

Tabela 3. Variáveis utilizadas para o cálculo do momento ótimo de substituição do Harvester John Deere, modelo 1270D, com valores em US$1.000,00. VR = Valor Residual; CI = Custo do Investimento; CO = Custo Operacional; COA = Custo Operacional Acumulado; CTM = Custo Total Médio; CIA = Custo do Investimento Atual; COA = Custo Operacional Atual; COAA = Custo Operacional Atual Acumulado; CTA = Custo Total Atual; EAC = Custo Anual Equivalente

Period (a)	VR (b)	CI (c)	CO (d)	COA (e)	CTM [(c+e)/a] (f)	CIA (g)	COA (h)	COAA (i)	CTA [(c+f)] (j)	EAC (k)
1	613.68	158.90	301.62	301.62	460.52	147.13	279.28	279.28	426.41	460.52
2	487.46	285.11	333.13	634.76	459.93	244.44	285.61	564.89	809.33	453.85
3	387.20	385.37	360.90	995.65	460.34	305.92	286.49	851.38	1,157.30	449.07
4	307.57	465.01	386.32	1,381.98	461.75	341.79	283.96	1,135.34	1,477.13	445.98
5	244.31	528.26	410.09	1,792.06	464.07	359.53	279.10	1,414.44	1,773.97	444.30
6	194.06	578.51	432.57	2,224.64	467.19	364.56	272.60	1,687.03	2,051.59	443.79
7	154.15	618.42	454.04	2,678.68	471.02	360.84	264.93	1,951.96	2,312.81	444.23
8	122.44	650.13	474.66	3,153.34	475.43	351.24	256.45	2,208.41	2,559.65	445.42
9	97.26	675.31	494.56	3,647.91	480.36	337.82	247.41	2,455.81	2,793.64	447.20
10	77.26	695.32	513.85	4,161.75	485.71	322.07	238.01	2,693.82	3,015.89	449.46

(column j of Table 4) equals the marginal revenue (column d of Table 4), which happens between 8 and 9 years.

3.5 Constant Replacement Chain Method

The optimal replacement time for the harvester follows the same marginal analysis principle used in the Terminal Cycle Method, meaning it occurs when its marginal cost (column l of Table 4) equals the marginal revenue (column d of Table 4). Therefore, it is observed that these values equalize between the seventh and eighth years (Figure 1).

Table 4. Variables used in the differential equations for calculating the optimal replacement time of the John Deere Harvester, model 1270D, based on the terminal cycle and substitution chain methods. Values in US$1,000.00. VR = Residual Value; CO = Operational Cost; RB = Gross Revenue; RL = Net Revenue; RLA = Current Net Revenue; RAA = Current Accumulated Revenue; LA = Current Profit; Va = Acquisition Value of the Harvester; iS= interest on resale value; S´= resale value variation (Vrt - Vrt-1); iB = profit on discounted value; Net Revenue = marginal revenue

Tabela 4. Variáveis utilizadas nas equações diferenciais para cálculo do momento ótimo de substituição do Harvester John Deere, modelo 1270D, com base no método do Ciclo Terminal e da Cadeita de Substituição. valores em US$1000,00. VR = Valor Residual; CO = Custo Operacional; RB = Renda Bruta; RL = Receita Líquida; RLA = Receita Líquida Atual; RAA = Receita Atual Acumulada; LA = Lucro Atual; Va = Valor de aquisição do Harvester; iS= juros sobre o valor de revenda; S´= variação do valor de revenda (Vrt - Vrt-1); iB = lucro sobre o valor descontado; Receita Líquida = receita marginal

Períod	VR (a)	CO (b)	RB (c)	RL (c-b) (d)	RLA (e)	RAA (f)	LA (f+a-Va) (g)	i.S (h)	S’ (i)	i.S + S’ (j)	i.B (k)	(i.S+S’)+iB (l)
1	613.68	301.62	523.17	221.55	205.14	205.14	46.24	49.09	158.90	207.99	3.70	211.69
2	487.46	333.13	523.17	190.04	162.93	368.06	82.95	39.00	126.22	165.21	6.64	171.85
3	387.20	360.90	523.17	162.27	128.82	496.88	111.51	30.98	100.26	131.23	8.92	140.15
4	307.57	386.32	523.17	136.85	100.59	597.46	132.46	24.61	79.64	104.24	10.60	114.84
5	244.31	410.09	523.17	113.08	76.96	674.43	146.16	19.54	63.26	82.80	11.69	94.50
6	194.06	432.57	523.17	90.59	57.09	731.52	153.00	15.52	50.25	65.77	12.24	78.01
7	154.15	454.04	523.17	69.13	40.34	771.85	153.43	12.33	39.91	52.24	12.27	64.52
8	122.44	474.66	523.17	48.51	26.21	798.06	147.93	9.80	31.70	41.50	11.83	53.33
9	97.26	494.56	523.17	28.61	14.31	812.37	137.06	7.78	25.18	32.96	10.96	43.93
10	77.26	513.85	523.17	9.32	14.32	816.69	121.37	6.18	20.00	26.18	9.71	35.89

**Va = Acquisition value of the Harvester; iS= interest on resale value; S´= resale value variation (Vrt - Vrt-1); iB = profit on discounted value; Net revenue = marginal revenue*

**Va = Valor de aquisição do Harvester; iS= juros sobre o valor de revenda; S´= variação do valor de revenda (Vrt - Vrt-1); iB = lucro sobre o valor descontado; Receita Líquida = receita marginal*

4. DISCUSSION

For the TAC method, the optimal replacement time for a machine occurs in the year when the TAC is at its minimum. In this study, this was observed at 2 years of harvester use. For this specific analysis, the methodology is inadequate because the replacement of a forestry machine typically occurs after a longer period of use, given current preventive and predictive maintenance routines (Diniz et al., 2020). This discrepancy is justified by the high acquisition and operational costs, and the method’s failure to consider capital

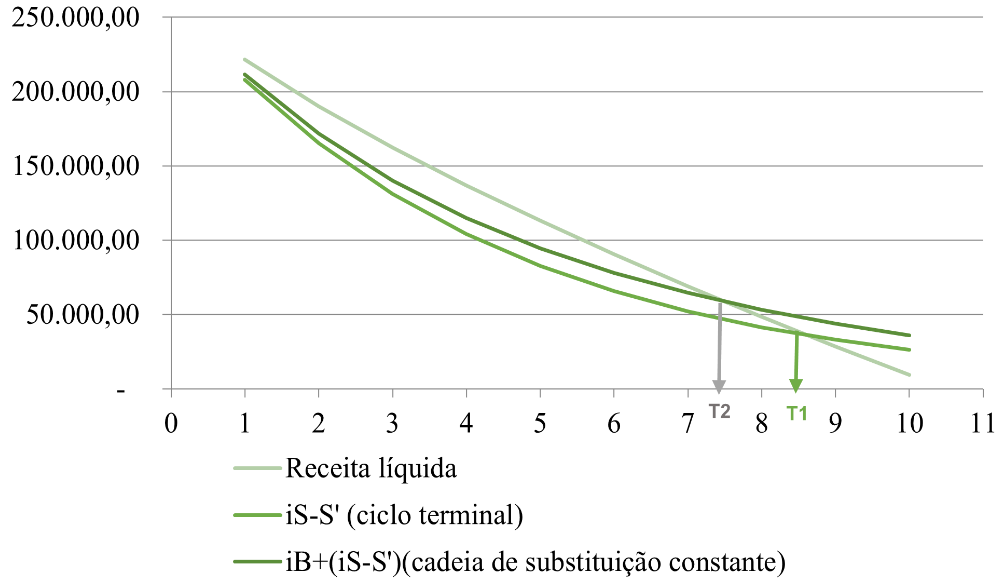

Figure 1. Optimal replacement time for the Harvester for the terminal cycle (T1) and for the substitution chain (T2)

Figura 1. Momento ótimo para substituição do Harvester para o ciclo terminal (T1) e para a cadeia de substituição (T2)

variation over time (interest rate) and the revenues or production of the harvester, which significantly impacts the analysis.

The EAC method, by using the discount rate, was more efficient than the TAC method and provided a result more consistent with the reality of the forestry sector. Moreover, it is the most widely used method in studies on machinery and equipment replacement, being simple, easy to apply, and efficient. Similar to the TAC method, the EAC did not consider the revenues generated by the machine during the analyzed periods. If the machine's revenues were considered, this method would be referred to as the Equivalent Annual Value (EAV) or the Equivalent Periodic Benefit (Cost) (EPB(C)). Revenues can alter the result or the optimal replacement time.

Bassoli et al. (2020), when evaluating the optimal replacement time for forestry harvest machines using the EAC, observed the optimal time starting from the 4th year of the machines' useful life. Additionally, the main costs affecting this result were the costs of parts replacement and maintenance. The decision to replace or not replace the machine rests with the managers; however, in this case, it is important to note that the equivalent uniform cost for the 5th year of the machine's useful life would increase by 18.3%. The analysis for replacing another machine used in forestry harvesting operations also returned a result similar to that observed in the present study, with a recommendation for replacement at 5 years of useful life, with 90% of the costs being maintenance, repairs, labor, fuel, and depreciation (Santos et al., 2016b), which were also the main costs in the present study.

Still using the EAC method, the optimal time for replacing a forestry harvest machine was not observed, as the equivalent uniform annual cost was increasing, but the company had an internal recommendation to replace the machinery at 5 years of useful life (Simões et al., 2013). This can occur because some assets may not reach the optimal replacement time due to the increasing trend of the equivalent annual cost curve (Cesca, 2018). It is crucial to emphasize that operations managers have defined appropriate times for machinery replacement based on the different realities of forestry harvesting operations in Brazil.

The Terminal Cycle Method assumes that the machine will be used for a certain period and then activities will cease, with no future cycles or activities. Thus, the replacement time tends to be extended compared to other methods, as the machine will be used longer to compensate for the initial investment. This can occur due to the reduction in the residual value of the machinery over the years, with a tendency to stabilize in its final period of use, and was observed when evaluating the optimal determination of vehicles for wood transportation, with the optimal replacement time at 9 years of useful life (Marques et al., 2005).

The Constant Replacement Chain Method considers that the machine, after a certain period of use, will be replaced by another, and so on, forming a chain. In this way, the cycles or links in the chain are interconnected over time, meaning they are dependent. The costs and revenues of the current and future cycles can affect the optimal replacement time, bringing forward the machine's replacement compared to the Terminal Cycle Method. This method is the most consistent with the reality of forestry sector companies, which have long production cycles, and the fleet of machines is replaced at specific time intervals (Camargo et al., 2022). Therefore, determining the useful life of a machine used in forestry harvesting from an economic perspective, or the period in which it performs its activities at the lowest operational cost, is directly related to the lowest production cost.

5. CONCLUSION

The four methods used differed in their indication of the optimal replacement time for the Harvester. Although the TAC is a very simple and well-known method, it does not lead to an appropriate result and should not be recommended for use in the case of the Harvester.

The EAC, in addition to being a simple method, has been widely used in economic studies because it considers costs, interest rates, period durations, and other variables. This method presented a result more consistent with the reality of forestry companies and can be used without major issues.

Methods that use continuous functions also provide consistent results but present different perspectives. The Terminal Cycle case is specific to situations where a company operates for a certain period, then sells the machine and ceases its activities. Thus, this method tends to extend the replacement time for the machine, which in the present study was between eight and nine years.

The constant replacement chain method provided a replacement time between seven and eight years, which is very consistent with the reality of forestry companies that practice forestry harvesting for an extended period. Therefore, this method can also be considered in decision-making, as it is a more robust method that considers the cost and revenue variables of the machine. Although these methods that use continuous functions have been described in the literature for a long time, they are not widely used or disseminated due to their greater computational complexity.

In this study, it was possible to determine the optimal time to replace the Harvester from an economic perspective. Although several technical characteristics of the machine were considered in calculating its operational cost, it is known that in practice, a series of other technical factors must be taken into account, which were not addressed here. Therefore, the economic optimum does not always coincide with the technical recommendations of manufacturers and mechanical technicians. Each case should be analyzed with great care and common sense to make the final decision.

AUTHOR CONTRIBUTIONS

Rodrigues, T. A., Silva, M. L. da & Leite, E. da S.: Conceptualization; Data curation; Formal Analysis; Writing – original draft. Silva, M. L. da, Schettini, B. L. S. & Silva, A. A.: Writing – original draft, review & editing. Minette, L. J.: Writing – review & editing.

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