Economical Assessment of Industrial Motor Replacement from the Perspective of Life Cycle Cost Analysis

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***Abstract*— The increasing concern about climate change has underpinned global efforts toward the reduction of greenhouse gas emissions (GHGs). In this sense, energy efficiency actions (EEAs) are interesting solutions that have been expanding over the years in the industrial sector. Replacing low-efficiency electric motors with high-efficiency counterparts is a ubiquitous action in this sense. However, they still have an excessive cost, making it necessary to perform a proper technical-economic analysis to determine the feasibility of the action. For this purpose, life cycle cost analysis (LCCA) has proven to be an excellent alternative for economic viability verification of EEAs because this methodology considers expenses throughout the entire life cycle of the project or equipment. Considering decision-making involving optimization, this work proposes a methodology to calculate the present residual value at the end of the life cycle, considering the service time of motors and the chosen study period for the project. Two case studies involving predicted theoretical situations are simulated, and the impact of service time on the replacement of a 50-CV, four-pole motor and, 40-CV in a local industry is assessed. It is observed that *Net Savings* are affected by the study period when replacement occurs in terms of a low-power high-efficiency motor since such action can lead to different service times. Overall, the improved LCC applied to induction motors replacement proves to be a good method for predicting the residual value, whereas the results show that different service times are necessary to maximize net savings and the residual cost in the same case.**

Link to graphical and video abstracts, and to code: https://latamt.ieeer9.org/index.php/transactions/article/view/8823

***Index Terms*— energy efficiency, industrial economics, life cycle cost, service time, three-phase induction motors.**

I. Introduction

THE industrial sector accounts for 32.3% of end electricity consumption in Brazil, with great potential for the application of energy efficiency actions (EEAs). The energy consumed by the currently operating driving force represents 68% of the total consumption. Overall, electric motors represent approximately 30% of the country's energy consumption. The three main EEAs in this scenario include the use of efficient drives (frequency converters, voltage regulators), matching the motor and load powers, and using high-efficiency motors [1].

In the context of standardization criteria and labeling procedures conducted on high-efficiency motors since 1993 [2], minimum energy performance standards (MEPSs) yielded a significant reduction in energy consumption. In 2002, with the Energy Efficiency Act already in force, three-phase induction motors were the first equipment to comply with minimum performance standards in Brazil [3]. In 2005, through Interministerial Ordinance No. 553/2005 of the Ministry of Mines and Energy (MME), the adoption of minimum efficiency levels for three-phase induction motors manufactured from December 2009 became mandatory with the introduction of two categories: standard and high-efficiency motors (equivalent to IE2) [4].

Ordinance no. 1 issued by the MME established in 2017 that the minimum efficiency level for three-phase induction motors with a squirrel-cage rotor should be of type IR3 (equivalent to premium or IE3). This ordinance came into effect in August 2019 [5]. Thus, it is reasonable to state that Brazil is undergoing an energy transition scenario in which such motors play a significant role. Therefore, the replacement of traditional motors in operation with high-efficiency counterparts is an acceptable practice, provided that: (I) the process follows the analysis of motor loading; (II) there is proper technical justification for the replacement with a motor with lower rated power; and (III) another concise criterion is used for the replacement [6].

Life cycle cost analysis (LCCA) is an economic assessment measure recommended by the US government for energy conservation and energy efficiency projects [7]. LCCA finds applications in various fields, including wind farm maintenance management [8], wind turbine converter selection [9], determining the most cost-effective transmission line installations [10], assessing the cost-effectiveness of naturally-ventilated industrial transformers compared to forced-air ones [11], economically measuring the impact of electric vehicle fleets in specific locations [12], sensitivity analysis of parameters on the optimal cost of photovoltaic water pumping systems [13], evaluating the viability of hybrid electric tractors for agriculture [14], and assessing the economic feasibility of energy efficiency public policies, among other applications [15] [16] [17].

The associate editor coordinating the review of this manuscript and approving it for publication was Eduardo M. G. Rodrigues (C*orresponding author: Victor Aguiar*).

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Recently, LCCA has emerged as a powerful tool in studies concerning SCIM replacement. It demonstrates the cost-effectiveness of various motor retrofitting methods, highlighting the rewinding [19].

Considering that the service period of motors varies according to the nominal power [19] [16] and that the replacement with high-efficiency units can be carried out while maintaining, reducing [20] [21], or even increasing the nominal power [6], the service times of low-efficiency and high-efficiency motors may differ in practice if the rated power of high-efficiency motor is reduced and has a different service time. These differences in service times are statistical measurements of motors populations in regions/countries for government use. Therefore, it may result in a residual value at the end of the life cycle cost analysis (LCCA), thus justifying economic studies on the subject.

In this context, the objective of this work is to determine the residual value in processes where low-efficiency motors are replaced with high-efficiency ones while taking the service times into account in the analysis. The latter parameter is crucial for investors as it quantifies the present value of the asset, providing relevant information for decision-making and partially addressing economic issues regarding estimating the resale value of reconditioned motors as mentioned in [5].

II. LCCA – Life Cycle Cost Analysis

LCCA is an economic evaluation tool that encompasses all costs associated with the life cycle of equipment or processes, making it an efficient method for assessing the feasibility of engineering actions. Economic feasibility study through LCCA occurs over periods. The time or study period is the duration during which the project's feasibility is assessed. In other words, this is the period over which a specific engineering action is analyzed from the economic viewpoint. The service time or period is the duration during which the engineering action is in operation [22]. Figure 1 represents the periods involved in LCCA.

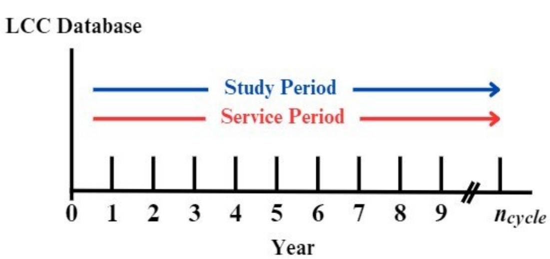

Fig. 1. Periods involved in LCCA [22].

The life cycle cost of a three-phase induction motor is given by (1).

$$C_{LCC} = C_I + C_E + C_{O\&M} + C_{rep} - C_{res}\,, \quad (1)$$

where C_I is the present value of the investment, C_E is the present value of the consumed energy cost, $C_{O\&M}$ is the present value of the operation and maintenance cost, C_{rep} is the present value of the replacement cost, and C_{res} is the present value of the residual cost at the end of the life cycle [19] [16] [7].

The energy cost C_E for supplying a three-phase induction motor is calculated from (2).

$$C_E = \frac{0.736\ \cdot P_n \cdot L \cdot T \cdot H}{\eta(L)}, \quad (2)$$

where P_n is the rated power in HP, L is the motor loading in pu, T is the electricity tariff in R$/kWh, H is the number of operating hours per year, and $\eta(L)$ is the motor efficiency as a function of loading [7].

To perform LCCA, it is necessary to represent costs in terms of the net present value (NPV). Thus, the NPV of electrical energy cost (NPV_{CE}) is represented in (3), where $\hat{e}$ is the real escalation rate, d is the discount rate, and n_{cycle} is the study period in years.

$$NPV_{CE} = \sum_{t=1}^{n_{cycle}} C_E \cdot \left(\frac{1+\hat{e}}{1+d}\right)^t \quad (3)$$

The NPV of the investment cost (NPV_{CI}) is obtained from (4).

$$NPV_{CI} = \frac{C_I}{(1+d)^t}\,, \quad (4)$$

where t is the investment period in years, also considering that an initial investment is required before the equipment operation begins, i.e., $t = 0$.

The remaining costs mentioned in (1) are neglected in this study. The only exception is residual cost, which will be calculated in the next section. This is a valid assumption because maintenance and replacement costs are considered to be the same for both low- and high-efficiency motors, yielding a net balance equal to zero in the economic feasibility analysis. This premise is reasonable given that the maintenance schedule for the motors is the same, while there is no technological discrepancy in the parts replaced in both cases.

III. Net Savings

Net savings is a supplementary economic performance measure calculated from the difference between the life cycle costs of the base and alternative cases, which consist of the low- and high-efficiency motors, respectively in this study [22]. Since costs are projected over a future study period, they are assessed in present value terms relative to the study's outset. Therefore, one can define net savings NS as in (5).

$$NS = NPV_{LE} - NPV_{HE}, \quad (5)$$

where NPV_{LE} and VPL_{HE} are the NPVs of the low-and high-efficiency induction motors, respectively.

IV. LCCA Applied in the Replacement of Induction Motors

A. This section addresses the application of LCCA in the replacement of low-efficiency motors with high-efficiency ones based on simple and straightforward criteria. The service time is assumed to be the same for both types of motors, but different from the study period. In addition, the economic feasibility analysis is carried out considering the net savings.

A. Service Times Shorter Than The Study Period

In this specific case, according to (3) and (4), the NPV of low-efficiency motors considering a service time m_{LE} shorter than n_{cycle} can be calculated from (6).

$$NPV_{LE} = \sum_{t=1}^{m_{LE}}\left[C_{E\_LE}\cdot\left(\frac{1+ê}{1+d}\right)^{t}\right] + I_{0\_LE} + \sum_{m_{LE}+1}^{n_{cycle}}\left[C_{E\_LE}\cdot\left(\frac{1+ê}{1+d}\right)^{t}\right] + I_{0\_LE}\cdot\left(\frac{1}{1+d}\right)^{m_{LE}} + \sum_{t=n_{cycle}+1}^{2\cdot m_{LE}}\left[C_{E\_LE}\cdot\left(\frac{1+ê}{1+d}\right)^{t}\right], \quad (6)$$

where C_{E_LE} and I_{0_LE} are the energy cost and investment cost of the low-efficiency motor, respectively. To complete the study period, it is necessary to purchase a new motor, and a new service time starts in $m_{LE}+1$, until $2.m_{LE}$.

Considering that the service time of high-efficiency motors m_{HE} is shorter than the study period, one can calculate NPV_{HE} from (7).

$$NPV_{HE} = \sum_{t=1}^{m_{HE}}\left[C_{E\_HE}\cdot\left(\frac{1+ê}{1+d}\right)^{t}\right] + I_{0\_HE} + \sum_{m_{HE}+1}^{n_{cycle}}\left[C_{E\_HE}\cdot\left(\frac{1+ê}{1+d}\right)^{t}\right] + I_{0\_HE}\cdot\left(\frac{1}{1+d}\right)^{m_{HE}} + \sum_{t=n_{cycle}+1}^{2\cdot m_{HE}}\left[C_{E\_HE}\cdot\left(\frac{1+ê}{1+d}\right)^{t}\right], \quad (7)$$

where C_{E_HE} and I_{0_HE} are the electrical energy cost and investment cost of the high-efficiency motor, respectively. To complete the study period, it is necessary to purchase a new motor, and a new service time starts in $m_{HE}+1$, until $2.m_{HE}$.

Substituting (6) and (7) in (5), as well as considering that both motors have the same service time $m_{LE} = m_{HE} = m$, one can calculate the net savings NS as in (8).

$$NS = \sum_{t=1}^{n_{cycle}}\left[\left(C_{E\_LE}-C_{E\_HE}\right)\cdot\left(\frac{1+ê}{1+d}\right)^{t}\right] + \left(I_{0\_LE}-I_{0\_HE}\right) + \left(I_{0\_LE}-I_{0\_HE}\right)\cdot\left(\frac{1}{1+d}\right)^{m} + \sum_{t=n_{cycle}+1}^{2\cdot m}\left[\left(C_{E\_LE}-C_{E\_HE}\right)\cdot\left(\frac{1+ê}{1+d}\right)^{t}\right]. \quad (8)$$

Considering the equalities in (9) and (10) and substituting both equations in (8) yields (11).

$$\Delta C_E = C_{E\_LE} - C_{E\_HE}, \quad (9)$$

$$\Delta I_0 = I_{0\_HE} - I_{0\_LE}, \quad (10)$$

$$NS = \sum_{t=1}^{n_{cycle}}\left[(\Delta C_E)\cdot\left(\frac{1+ê}{1+d}\right)^{t}\right] - (\Delta I_0) - (\Delta I_0)\cdot\left(\frac{1}{1+d}\right)^{m} + \sum_{t=n_{cycle}+1}^{2\cdot m}\left[(\Delta C_E)\cdot\left(\frac{1+ê}{1+d}\right)^{t}\right]. \quad (11)$$

Thus, it is observed that NS is composed of three terms as represented in (12)–(14).

$$CE = \sum_{t=1}^{m}\left[(\Delta C_E)\cdot\left(\frac{1+ê}{1+d}\right)^{t}\right] + \sum_{m+1}^{n_{cycle}}\left[(\Delta C_E)\cdot\left(\frac{1+ê}{1+d}\right)^{t}\right], \quad (12)$$

$$CI = (\Delta I_0) + (\Delta I_0)\cdot\left(\frac{1}{1+d}\right)^{m}, \quad (13)$$

$$CR = \sum_{t=n_{cycle}+1}^{2\cdot m}\left[(\Delta C_E)\cdot\left(\frac{1+ê}{1+d}\right)^{t}\right], \quad (14)$$

where CE is the net electrical energy cost, CI is the net investment cost, and CR is the net residual cost or active residual cost. In addition, equations (12)–(14) take into account that the service time is greater than half the study period, resulting in initial and intermediate investments.

B. Service Times Longer Than The Study Period

Using the same criterion adopted in Section IV.A, one can calculate the NPV for the low-efficiency motor corresponding to NPV'_{LE} considering that the service time differs from the study period ($n_{cycle} < m_{LE}$) from (15).

$$NPV'_{LE} = \sum_{t=1}^{n_{cycle}}\left[C_{E\_LE}\cdot\left(\frac{1+ê}{1+d}\right)^{t}\right] + I_{0\_LE} + \sum_{t=n_{cycle}+1}^{m_{LE}}\left[C_{E\_LE}\cdot\left(\frac{1+ê}{1+d}\right)^{t}\right]. \quad (15)$$

Similarly, the NPV for the low-efficiency motor corresponding to NPV'_{LE} considering $n_{cycle} < m_{HE}$ is defined in (16).

$$NPV'_{HE} = \sum_{t=1}^{n_{cycle}}\left[C_{E\_HE}\cdot\left(\frac{1+ê}{1+d}\right)^{t}\right] + I_{0\_HE} + \sum_{t=n_{cycle}+1}^{m_{HE}}\left[C_{E\_HE}\cdot\left(\frac{1+ê}{1+d}\right)^{t}\right]. \quad (16)$$

Substituting (15) and (16) in (5), also considering (9) and (10), and assuming that the low- and high-efficiency motors have the same service time ($mbr = mar = m'$) gives (17)–(19).

$$CE' = \sum_{t=1}^{n_{cycle}}\left[(\Delta C_E)\cdot\left(\frac{1+ê}{1+d}\right)^{t}\right], \quad (17)$$

$$CI' = \Delta I_0, \tag{18}$$

$$CR' = \sum_{t=n_{cycle}+1}^{m'} \left[(\Delta C_E) \cdot \left(\frac{1+ê}{1+d} \right)^t \right], \tag{19}$$

where CE' is the net electrical energy cost, CI' is the net investment cost, and CR' is the net residual cost or active residual cost.

V. Differences between the Service Times of Motors and the Study Period

This section presents the LCCA applied in three case studies while considering distinct service times for the motors and study time.

A. Case 1: $m_{HE} < m_{LE} < n_{cycle}$

Using the same criteria adopted in Section IV, one can calculate NPV_{LE} and NPV_{HE} from (6) and (7), respectively, considering that the service time differs from the study period. Fig. 2 shows the service times of the assessed motors.

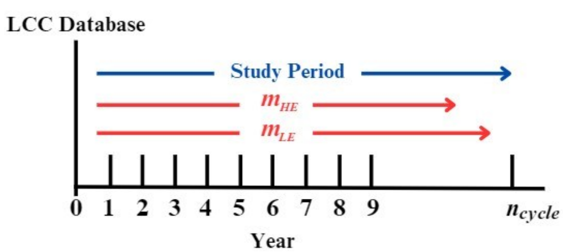

Fig. 2. Service times defined for case 1.

Substituting (6) and (7) in (5) and considering $m_{HE} < m_{LE} < n_{cycle}$ gives (20)–(22).

$$CE_1 = \sum_{t=1}^{n_{cycle}} \left[(\Delta C_E) \cdot \left(\frac{1+ê}{1+d} \right)^t \right], \tag{20}$$

$$CI_1 = (\Delta I_0) - (I_{0\_LE}) \cdot \left(\frac{1}{1+d} \right)^{m_{LE}} + (I_{0\_HE}) \cdot \left(\frac{1}{1+d} \right)^{m_{HE}}, \tag{21}$$

$$CR_1 = \sum_{t=n_{cycle}+1}^{2 \cdot m_{HE}} \left[(\Delta C_E) \cdot \left(\frac{1+ê}{1+d} \right)^t \right] + \sum_{t=2 \cdot m_{HE}+1}^{2 \cdot m_{br}} \left[C_{E\_LE} \cdot \left(\frac{1+ê}{1+d} \right)^t \right], \tag{22}$$

where CE_1 is the net electrical energy cost, CI_1 is the net investment cost, and CR_1 is the net residual cost or active residual cost.

This section considers that the service times of both motors are longer than half the study period, yielding initial and intermediate investments for the accurate calculation of residual value.

B. Case 2: $m_{HE} < n_{cycle} < m_{LE}$

In this case, one can determine the NPV for the low-efficiency motor NPV_{LE2} from (3) and (4) considering $m_{HE} < n_{cycle} < m_{LE}$, resulting in (23). Fig. 3 shows the intervals associated with the LCCA for case 2.

$$NPV_{LE2} = \sum_{t=1}^{m_{HE}} \left[C_{E\_LE} \cdot \left(\frac{1+ê}{1+d} \right)^t \right] + I_{0\_LE} + \sum_{t=m_{HE}+1}^{n_{cycle}} \left[C_{E\_LE} \cdot \left(\frac{1+ê}{1+d} \right)^t \right] + \sum_{t=n_{cycle}+1}^{m_{HE}} \left[C_{E\_LE} \cdot \left(\frac{1+ê}{1+d} \right)^t \right]. \tag{23}$$

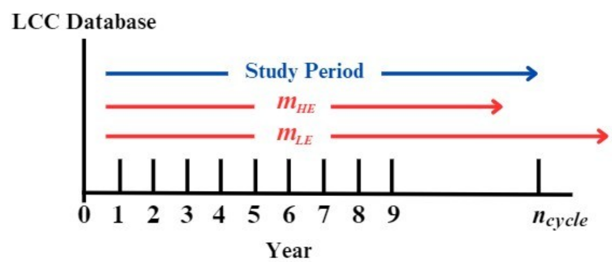

Fig. 3. Service times defined for case 2.

The NPV for the high-efficiency motor NPV_{HE2} considering $m_{HE} < n_{cycle} < m_{LE}$ is given by (24).

$$NPV_{HE2} = \sum_{t=1}^{m_{HE}} \left[C_{E\_HE} \cdot \left(\frac{1+ê}{1+d} \right)^t \right] + I_{0\_HE} + \sum_{m_{HE}+1}^{n_{cycle}} \left[C_{E\_HE} \cdot \left(\frac{1+ê}{1+d} \right)^t \right] + I_{0\_HE} \cdot \left(\frac{1}{1+d} \right)^{m_{HE}} + \sum_{t=n_{cycle}+1}^{2 \cdot m_{HE}} \left[C_{Ear} \cdot \left(\frac{1+ê}{1+d} \right)^t \right]. \tag{24}$$

Substituting (23) and (24) in (5), one can determine *NS*, which consists of the terms defined in (25)–(27).

$$CE_2 = \sum_{t=1}^{n_{cycle}} \left[(\Delta C_E) \cdot \left(\frac{1+ê}{1+d} \right)^t \right], \tag{25}$$

$$CI_2 = (\Delta I_0) + (I_{0\_HE}) \cdot \left(\frac{1}{1+d} \right)^{m_{HE}}, \tag{26}$$

$$CR_2 = \sum_{t=n_{cycle}+1}^{m_{LE}} \left[(\Delta C_E) \cdot \left(\frac{1+ê}{1+d} \right)^t \right] - \sum_{t=m_{LE}+1}^{2 \cdot m_{HE}} \left[C_{E\_HE} \cdot \left(\frac{1+ê}{1+d} \right)^t \right], \tag{27}$$

where CE_2 is the net electrical energy cost, CI_2 is the net investment cost, and CR_2 is the net residual cost or active residual cost.

It is noteworthy that the equations were derived for the specific case in which the service time of the high-efficiency motor is shorter than the study period, yielding initial and intermediate investments.

C. Case 3: $n_{cycle} < m_{HE} < m_{LE}$

Using the same criteria adopted in Sections V.A and V.B, one can determine the NPV for the low-efficiency motor NPV_{LE3} considering $n_{cycle} < m_{LE}$ from (28). Fig. 4 shows the intervals associated with the LCCA for case 3.

$$NPV_{LE3} = \sum_{t=1}^{n_{cycle}} \left[C_{E\_LE} \cdot \left(\frac{1+\hat{e}}{1+d}\right)^t \right] + I_{0\_LE} + \sum_{t=n_{cycle}+1}^{m_{LE}} \left[C_{E\_LE} \cdot \left(\frac{1+\hat{e}}{1+d}\right)^t, \right] \tag{28}$$

Similarly, one can calculate the NPV for the high-efficiency motor NPV_{HE3} considering $n_{cycle} < m_{HE}$ from (29).

$$NPV_{HE3} = \sum_{t=1}^{n_{cycle}} \left[C_{E\_HE} \cdot \left(\frac{1+\hat{e}}{1+d}\right)^t \right] + I_{0\_HE} + \sum_{t=n_{cycle}+1}^{m_{HE}} \left[C_{E\_HE} \cdot \left(\frac{1+\hat{e}}{1+d}\right)^t \right] \tag{29}$$

Substituting (28) and (29) in (5), it is possible to determine NS from (30).

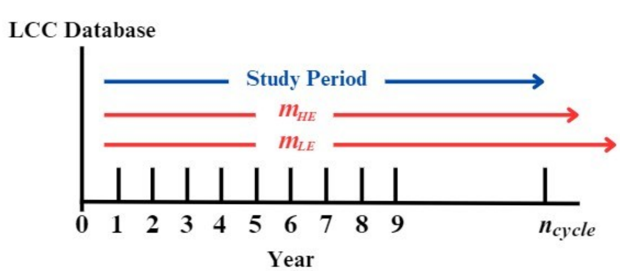

Fig. 4. Service times defined for case 3.

$$NS_3 = \sum_{t=1}^{n_{cycle}} \left[(\Delta C_E) \cdot \left(\frac{1+\hat{e}}{1+d}\right)^t \right] - (\Delta I_0) + \sum_{t=n_{cycle}+1}^{m_{HE}} \left[(\Delta C_E) \cdot \left(\frac{1+\hat{e}}{1+d}\right)^t \right] + \sum_{t=m_{HE}+1}^{m_{LE}} \left[C_{E\_HE} \cdot \left(\frac{1+\hat{e}}{1+d}\right)^t \right] \tag{30}$$

The terms that constitute (30) can be determined from (31)–(33).

$$CE_3 = \sum_{t=1}^{n_{cycle}} \left[(\Delta C_E) \cdot \left(\frac{1+\hat{e}}{1+d}\right)^t \right] \tag{31}$$

$$CI_3 = (\Delta I_0) \tag{32}$$

$$CR_3 = \sum_{t=n_{cycle}+1}^{m_{HE}} \left[(\Delta C_E) \cdot \left(\frac{1+\hat{e}}{1+d}\right)^t \right] + \sum_{t=m_{HE}+1}^{m_{LE}} \left[C_{E\_LE} \cdot \left(\frac{1+\hat{e}}{1+d}\right)^t \right] \tag{33}$$

VI. Methodology

From the equations presented in Section IV, it is possible to perform a techno-economic feasibility analysis for distinct service times of the motors, aiming to determine the residual value. Thus, the methodology employed in this work consists of analyzing the replacement of motors with different service times and comparing the results with the replacement of motors with identical service times. For this purpose, based on [7-8], it was found that the average service times of the 50-CV and 40-CV motors are 25 and 20 years in Brazil, respectively. To meet this requirement, three case studies (**CS**) were simulated, where the first and second **CS** (**CS A** and **CS B**) are about motor replacement in Brazil and the third, **CS C**, is a 40-CV and 60-CV motor replacement in Europe. The service time in this region is about 15 years:

- **CS A**: Replacement of a low-efficiency 50-CV motor (IR2) with a high-efficiency 40-CV motor (IR3), whereas the motors have different service times;
- **CS B**: Replacement of a low-efficiency 50-CV motor (IR2) with a high-efficiency 50-CV motor (IR3), whereas the motors have identical service times and,
- **CS C**: Replacement of a low-efficiency 40-CV motor (IE2) with a high-efficiency 60-CV (IE3), whereas the motors have identical service times.

The technical data of the motors regarding loading, efficiency, and rated current are provided in [9-10] and presented in Table I and II. Data regarding motor costs and their respective service times are available in [7-8] and presented in Table III and IV. In Table IV, an unusual discount rate of 5% is observed in economic analysis. However, it's maintained 5% because the case study carried out in [19] presents 5% as the discount rate used in the economic analyses carried out in the paper (Europe). Additionally, the exchange rate between dollars and reais is R$ 5.18 for every $1.00 plus 3% of the transaction value, resulting in the parameter summarized in Table I.

TABLE I
ELECTRICAL PARAMETERS OF THE THREE-PHASE INDUCTION MOTORS IN **CS A** AND **CS B**

Motor Type	Rated Power (CV)	Service Time (years)	Current (A)	Loading (pu)	Efficiency (%)	Cost (US$)	Cost (R$)
IR2 / four poles	50	25	37.96	0.481	91.05%	3383.74	18,053.61
IR3 / four poles	40	20	34.09	0.531	92.70%	3601.46	19,215.23
IR3 / four poles	50	25	36.46	0.424	92.40%	3992.81	21,303.24

TABLE II
ELECTRICAL PARAMETERS OF THE THREE-PHASE INDUCTION MOTORS IN **CS C**

Motor Type	Rated Power (CV)	Service Time (years)	Current (A)	Loading (pu)	Efficiency (%)	Cost (US$)	Cost (R$)
IE2 / four poles	40	15	-	0.923	91.04%	3275.92	17,478.34
IE3 / four poles	60	15	-	0.616	95.72%	4986,96	26,607.42

Economic quantities such as the escalation rate, discount rate, and the industrial electrical energy tariff in the Brazilian Northeast region are presented in [19] [16] [21] [7] and in Table III. The escalation rate $\hat{e}$ adopted in the present study is the one adopted in the Brazilian Northeast region, while the average tariff was determined from updated data [9-10]. Additionally, the discount rate used is the one recommended for energy efficiency actions, which is equal to 12% [23]. Table III presents the aforementioned data for **CS A** and **CS B** and Table IV presents European economic data available for **CS C** in this situation.

The operating cycle of the motor is four thousand hours per year, considering a daily regime of around 12 hours per day [9-10] [7].

VII. RESULTS AND DISCUSSION

After collecting the aforementioned data, the net savings were calculated for three different study periods: 15, 22, and 30 years. The equations from Sections IV and V were used for analyzing the **CS** defined in Section VI considering the service time of the motors and the study period for each condition. Tables V, VI and VII show the results obtained, while Tables VIII, IX and X present the costs involved in LCCA for the assessed cases.

TABLE III
ECONOMIC QUANTITIES ADOPTED FOR **CS A** AND **CS B**

Escalation Rate (Northeast Region, Industrial Class) (%)	Discount Rate (%)	Average Energy Tariff (R$ / kWh)
2.35%	12.00%	0.45608

Analyzing CS A in accordance with Tables V and VIII, where the service time of the low-efficiency motor is longer than that of the high-efficiency motor, it is observed that the net savings vary according to the study period.

TABLE IV
ECONOMIC QUANTITIES ADOPTED FOR **CS C**

Escalation Rate (EU, Industrial Class) (%)	Discount Rate (%)	Average Energy Tariff (R$ / kWh)
2.91%	5.00%	0.80

The study periods of 15 and 30 years showed satisfactory results. However, the 22-year period yielded net savings relatively lower than its counterparts.

TABLE V
NET SAVINGS CALCULATED FOR **CS A**

50-CV Motor (IR2) – 40-CV Motor (IR3)	
Study Period	**Net Savings**
15 years	R$ 48,345.29
22 years	R$ 21,971.31
30 years	R$ 39,780.44

As for the costs, a high residual value is observed for the 15-year study period, as well as a negative residual value for the 22-year period. Because the study period is shorter than the service times of the motors, it yields a potential asset for the motors represented in terms of the residual cost.

In the second case, requiring a second investment in the high-efficiency motor, followed by the study period ending in two subsequent periods, leads to a negative impact on the residual cost.

The results for **CS B** are given in Tables VI and IX, where the service time of the low-efficiency motor is equal to that of the high-efficiency motor. It is observed that the net savings are marginally influenced by the study period. However, the residual cost changes based on the study period, resulting in lower costs as the study period is extended beyond the service time. The asset value at the end of the cycle can influence decision-making and serve as a benchmark to determine the ideal study period for maximizing net savings.

TABLE VI
NET SAVINGS CALCULATED FOR CS B

50-CV Motor (IR2) – 50-CV Motor (IR3)	
Study Period	**Net Savings**
15 years	R$ 34,155.23
22 years	R$ 36,065.92
30 years	R$ 35,874.76

Finally, the results for **CS C** are shown in Tables VII and X. The net savings shows a valuable cost-effectiveness. One explanation is the high efficiency of the IE3 motor compared to the 40-CV motor, even with low load. Furthermore, In the year 15 and year 30 there is no residual cost. This happens because the service time of the motors are the same in year 15, and in year 30 there the same situation occurs (would be a second life cycle cumulatively on analysis).

TABLE VII
NET SAVINGS CALCULATED FOR **CS C**

40-CV Motor (IE2) – 60-CV Motor (IE3)	
Study Period	**Net Savings**
15 years	R$ 51,313,40
22 years	R$ 91,479.80
30 years	R$ 91,479.80

TABLE VIII
COSTS INVOLVED IN LCCA FOR **CS A**

50-CV Motor (IR2) – 40-CV Motor (IR3)			
Study Period	***CE***	***CI***	***CR***
15 years	R$ 32,772.93	R$ 1,161.62	R$ 16,733.99
22 years	R$ 36,784.96	R$ 3,153.60	R$ - 11,660.05
30 years	R$ 38,760.42	R$ 2,091.63	R$ 3,111.66

TABLE IX
COSTS INVOLVED IN LCCA FOR **CS B**

50-CV Motor (IR2) – 50-CV Motor (IR3)			
Study Period	***CE***	***CI***	***CR***
15 years	R$ 32,481.82	R$ 3,249.63	R$ 4,923.04
22 years	R$ 36,458.22	R$ 3,586.51	R$ 2,857.33
30 years	R$ 38,416.13	R$ 3,440.79	R$ 899.42

TABLE X
COSTS INVOLVED IN LCCA FOR **CS C**

40-CV Motor (IE2) – 60-CV Motor (IE3)			
Study Period	***CE***	***CI***	***CR***
15 years	R$ 59,868.60	R$ 3,249.63	R$ 0.00
22 years	R$ 82,197.67	R$ 12,670.40	R$ 21,952.52
30 years	R$ 104,150.20	R$ 12,670.40	R$ 0.00

VIII. CONCLUSION

This work has presented a mathematical framework that extracts, from real case studies involving different service times evaluated in an economic analysis, a study period that maximizes net savings and residual cost, the latter being a key factor in determining the resale costs of refurbished motors. A methodology for calculating the residual value considering a hypothetical situation in which low-efficiency motors replace high-efficiency ones was presented. Three case studies were assessed in detail: the simple and straightforward replacement of a motor with another with the same power ratings and high efficiency (**CS B**); replacement of a low-efficiency motor with another with a lower rated power (**CS A**) and replacement of a low-efficiency motor with another with higher rated power (**CS C**).

It has been demonstrated that the chosen study period for economic analysis directly influences the metrics, as well as the service time of the motors used in the process. **CS A** considers a study period of 22 years, that is, longer and shorter than the service times of the low- and high-efficiency motors corresponding to 25 and 20 years, respectively. Under this condition, net savings are the lowest, while the residual cost is negative. In turn, the analysis of **CS B**, in which the motors have the same service time, net savings change little, while the shorter the study period, the higher the residual cost. Looking for **CS C** the motors service time are equals, the residual cost is high in the beginning of motor's lifespan, and it decreases up to zero where service time is equal to study period.

The necessity for a more comprehensive simulation arises from these preliminary results. This involves varying the study period year by year to derive a function and subsequently identify the maximum and minimum values for net savings and residual cost. Since this exceeds the scope of the present study, evaluating the motor replacement technique outlined in [6] will be the focus of future research. Consequently, additional data can be collected, enabling investors to monetize the asset value over their desired period.

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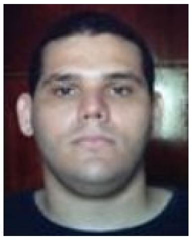

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