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AN IMPROVED STRATEGY BASED ON A MULTI-CRITERIA ANALYSE TO REPLACE TRANSFORMERS IN ELECTRIC DISTRIBUTION NETWORKS

BY

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Abstract. The new European legislation imposed through the Eco-Design Regulation from June 11, 2014, the maximum level of losses for transformers put into operation from July 1, 2015. This regulation has two main objectives: increasing the energy-efficiency (the first stage in 2015 / second stage in 2021) and improving the continuity in the electricity supply. In these conditions, the Distribution Network Operators (DNOs) began to develop strategies that consider these objectives. In the paper, a multi-criteria analysis-based strategy containing two decision-making levels is proposed to help the Decision-Maker (DM) in the replacement process of the old transformers. In the first stage, the transformers are classified, using the K-means clustering algorithm, in categories with replacement priorities assigned in function by the loading level and the commissioning year. A replacement ranking is established in the second stage based on a multi-criteria analysis, considering the energy-saving and power reserve. A transformer fleet with 114 units has represented the database in the testing of the proposed strategy. The obtained results highlighted an increase of the power reserve by 27% and the energy-saving by 39%, compared with the initial situation.

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Keywords: Eco-Design; decision-making; strategy; clustering techniques; multi-criteria analysis; aged transformers replacement.

1. Introduction

The power quality indicators associated with the electricity distribution service represents an essential benchmark in the establishment of the technical-economic solutions regarding the modernization/ development planning of the electrical distribution networks (EDNs) to ensure the transition towards the smart grids. These solutions will influence the economic efficiency of end-users' activity (consumers, prosumers, and electricity producers).

The energy efficiency is one of the three priorities within the "Europe 2030" strategy, alongside reducing greenhouse gas emissions and increasing the share of electricity produced from renewable sources in gross final energy consumption. Through the objectives assumed in the field, for example, Romania should contribute to the achievement of the target accepted at the level of the European Union (EU) on energy efficiency through the following values: primary energy consumption of a maximum 1273 Mtoe and 956 Mtoe of final energy. Thus, the global target is at least 32.5% at the EU level, an objective that can be revised upwards in 2023 (European Commission, 2019). Fig. 1 presents the main measures identified by the DNOs to improve energy efficiency in the EDNs in the various levels: electric distribution substations, lines, transformers, and consumers (ANRE, 2019).

Levels			
Electric distribution substations	**Lines**	**Transformers**	**Consumers**
Replacing the measurement groups	Phase load balancing	Interchanging the power transformers	Integration in the Smart Metering System
Modernization/ Replacement	Reconfiguration/ optimization	Change of the transformer taps	Modernization of the branching
	Modernization/ Replacement of the overhead lines and cables	Replacement of the MV/LV transformers	

Fig. 1 – The energy efficiency measurements at the various levels of the EDNs.

In the paper, the replacement of the distribution transformers with outdated performance standards, still in operation of the EDNs, will be treated.

The measure is presented in all energy efficiency programs of the DNOs from Romania due to the aging of the transformer fleet and, on the other hand, to respect the Eco-design Directive of the European Commission (European Commission, 2014). The replacement strategies applied by the DNOs should take into account the following objective (De Wachter, 2017):

- ***Increasing energy performance***. The analysis of operating the transformers with outdated energy performances highlighted that the cost of losses is higher than the initial investment. For this reason, those transformers with high losses, even if they work very well, must be replaced with units having the standards indicated by the European directives to increase the energy efficiency in the EDNs.
- ***Optimal loading of the transformer***. The loading can decrease or increase due to the dynamic variation of the demand, leading to an underloading or overloading of the transformer with undesirable effects on the energy losses.
- ***Improving the reliability and power quality indicators***. A failure in a transformer leads to the power supply interruption of all consumers from the area having undesirable effects on the performance indicators of the electricity distribution service.
- ***Prioritization in the replacement process***. The replacement of all transformers from the EDNs leads to high investments of the DNOs. For example, Table 1 presents the flat of distribution transformers corresponding to the DNOs from Romania containing 72156 units from which 44% exceeded their lifetime (ANRE, 2018). Thus, the DNOs must consider a replacement ranking that leads to the maximum technical and economic benefits.

Table 1

Flat of Distribution Transformers of the Romanian DNOs (*ANRE*, *2018*)

DNOs	before 1960	1960-1979	1980-1999	After 2000	Total
E-Distribuţie Muntenia S.A.	50	1154	783	6445	8432
E-Distribuţie Banat S.A.	489	4707	1792	1155	8143
E-Distribuţie Dobrogea S.A.	97	2925	1620	1498	6140
Distributie Energie Oltenia S.A.	148	5321	2187	2718	10374
Delgaz Grid S.A.	-	3199	5207	2699	11105
SDEE Electrica Muntenia Nord S.A.	202	5098	2926	1917	10143
SDEE Transilvania Nord S.A.	209	4003	2666	1976	8854
SDEE Transilvania Sud S.A.	835	3219	1895	3016	8965
Total (units)	2030	29626	19076	21424	72156
Total (%)	3%	41%	26%	30%	100%

Many studies evaluated the impact of the EU Directive implementation on energy saving. These have different assumptions referring to the analysis type (theoretical or practical). An analysis is done in (Pezzini *et al*., 2010), in the case of a DNO from Spain, based on an optimization model with a single objective referring to maximize energy efficiency. The solution was determined using linear programming, taking different levels of energy performance into account. (De Almeida *et al*., 2016) evaluated the impact of the efficient distribution transformers recommended by the EU Directive having as objective the replacing the worst transformers from the market. The study was theoretically considering the 50% loading for all transformers, without considering the real data, to estimate the energy saving. Also, (Tpeer and Carlen, 2015) studied the same theoretical implications of the replacement process using the small, medium, and large power transformers. For a 1000 kVA dry transformer, a detailed analysis based on the environmental benefit and the reduction in life cycle costs highlighted the economic benefits. Also, the producers have pointed out the economic benefits in their reports (ABB, 2014) and (Siemens, 2015). The comparison is considered based on the best available manufacturing technology (Tier 1).

(Mihai *et al*., 2010) used the real data, provided by a DNO from Romania, to identify the benefits of reducing the energy losses. However, the authors did not consider an optimization process to determine the optimal loading of new transformers keeping the same rated powers. The approaches presented in (Reider *et al*., 2015; Grigoraş *et al*., 2017) highlighted the importance of resizing into the replacement process to obtain additional energy savings. (Chelaru and Grigoraș, 2020) proposed an expert system which to identify the replacement solutions based on the loading factor and commissioning year, but without to use an optimization process.

From all analyses, it can observe that there aren't strategies based on the classification in the categories with priority degrees in the replacement process. Also, the studies and reports did not present a complete evaluation of the energy performance through identifying the optimal solutions which to satisfy more objectives such as the energy-saving, power reserve (resulted from the optimal loading), and continuity in the electricity supply quantified through various indicators: System Average Interruption Duration Index - SAIDI, System Average Interruption Frequency Index – SAIFI or Average Service Availability – ASA (ANRE, 2016b).

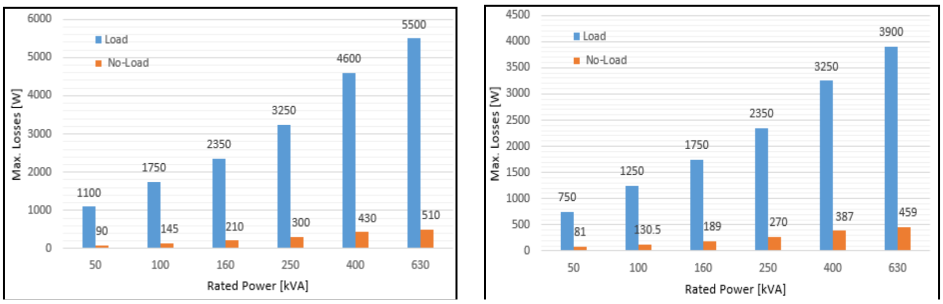
In the paper, a decision-making strategy based on a multi-criteria analysis is developed to replace the aged transformers in electric distribution networks, starting from the state of the transformers fleet belonging to the DNOs from Romania. In the first stage, the transformers are classified, considering the loading level and the commissioning year as input data in a clustering process. Each category will have a certain priority degree that influences the replacement order of transformers in the second stage. The replacement ranking is finally established based on a multi-criteria analysis considering the energy-saving and power reserve. According to (Miettinen, 1999), multi-criteria optimization is included in the decision-making area which treats optimization problems having more than one objective to be performed simultaneously.

The structure of the paper is the following: Section 2 gives information about the performance standards of the transformers from the UE countries; Section 3 details the steps of proposed replacement decision-making strategy; Section 4 presents the results obtained in the case of a fleet with 114 transformers belonging a DNO from Romania and Section 5 highlights the conclusions and the future work.

2. Performance Standards in the EU

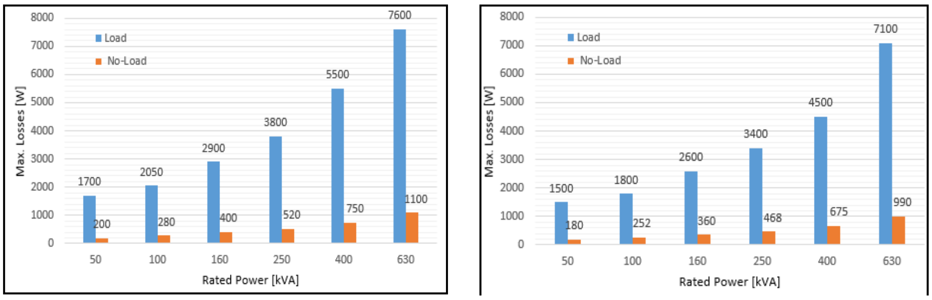
The Eco-Design Regulation is applied since 2014 and published in the Official Journal of the EU. The new legislation imposes within the EU countries the maximum level of losses for the power transformers put into operation from July 2015, applies to the power transformers purchased after June 11, 2014. The manufactured transformers after July 1, 2015, without these minimum requirements, cannot be introduced by the DNOs in the networks, and the producers will be fully responsible for the law enforcement. The accomplishment of this directive in the EU countries should lead to a decrease in the loss levels due to using high-quality materials, especially for the magnetic core (to obtain smaller losses). The efforts are focused on the optimal loading of the transformers to have low no-load losses for the small loadings and low load losses for the higher loadings of transformers, regardless of the rated power. Ideally, the transformers should operate at the optimal loading (the load and no-load losses are equal).

The load and no-load losses in the case of liquid-filled power transformers in the range 50 – 630 kVA of the rated power, put into service after July 1, 2015 (Tier 1), are presented in Fig. 2*a*.



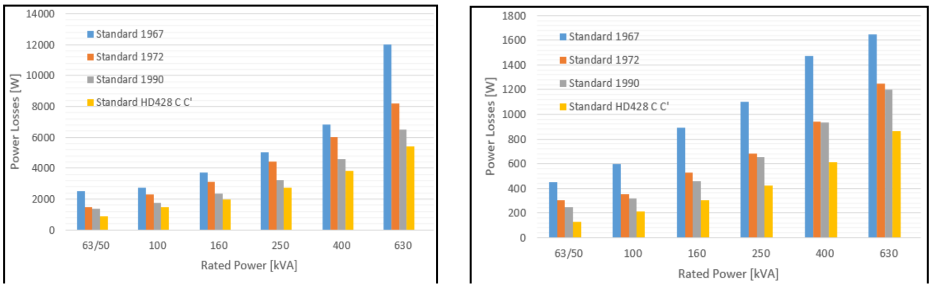
a *b*

Fig. 2 – The power losses of the liquid-filled power transformers:
a – Tier 1 (after July 1, 2015); *b* – Tier 2 (after July 1, 2021).



a *b*

Fig. 3 – The power losses of the cast resin power transformers:
a – (Tier 1 - after July 1, 2015); *b* – (Tier 2 - after July 1, 2021).



a *b*

Fig. 4 – Comparison between the power losses of the liquid-filled distribution transformers with different performance standards
a – Non-load losses; *b* – load losses.

The lowest values of the power losses will be found in power transformers built starting July 2021 (Tier 2), as seen in Fig 2*b*. The cast resin transformers have other power losses (a bit higher), as seen in Figs. 3*a* (Tier 1) and 3*b* (Tier 2). The Tier 2 technology compared with Tier 1 has the load losses lower by about 29% and the no-load losses by 10%.

The values from Fig. 4 corresponds to the whole spectrum of performance standards of the power transformers still operated by the DNOs from Romania. They emphasize high differences between the power losses associated with the performance standards 1967 and HD428CC′, where C refers to the load losses and C′ to the non-load losses. The rated powers of 40 and 63 kVA have been replaced by 50 kVA starting with the HD428CC′ performance standard. Regarding the fleet of power transformers with the commissioning year before 1990, the number is high, as it results from the reports of DNOs from Romania at the level of the 2018 year, see Table 1.

3. Multi-Criteria Analysis-based Decision Making Strategy

The transformers' replacement strategy proposed in this paper integrates a methodology with two stages characterized by a decision-making process, as presented below. Fig. 5 shows the flow-chart used to implement the strategy at the DNOs.

The information corresponding to the loading level and the commissioning year, provided by the DNO, is used to classify the transformers in the first stage. The input data assigned to each transformer are recorded in a matrix [*T*] containing two elements on each row: the commissioning year, *YC*, and the transited power at the peak load, S_{max}, calculated based on the phase currents and voltages recorded in a database with measurements of the DNO. The matrix [*T*] has the size (N_{TR} x2), where N_{TR} represents the number of analysed transformers. The elements will be normalized using proper factors. The "Tier 1" performance standard will be used as a reference for the commissioning year and rated power for the maximum transited power.

The K-means clustering algorithm (Grigoraş *et al*., 2016; Hossain *et al*., 2019; Wang *et al*., 2017) is used to achieve categories characterized by a priority degree in the replacement process.

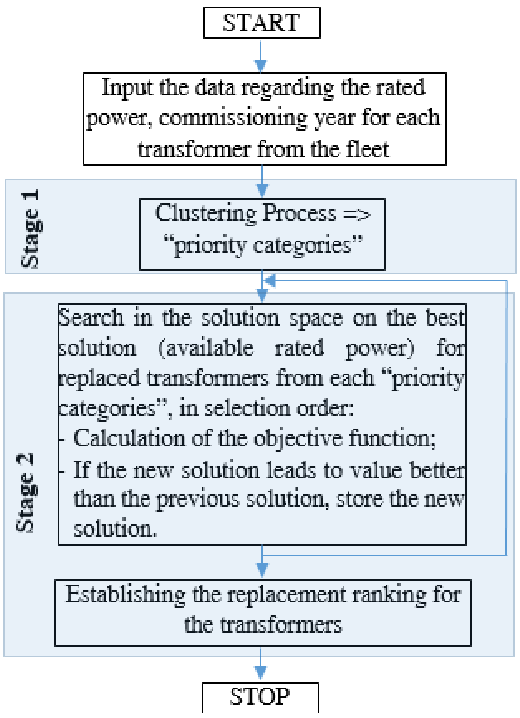


Fig. 5 – Flow-chart of the proposed methodology.

The algorithm was chosen due to its robustness and efficiency in obtaining the representative partitions (clusters), very well defined (Fränti and Sieranoja, 2019; Sinaga, 2020). The solution refers to an optimal number of clusters following an optimization process. The minimization of a sum, associated with the Euclidean distances between elements and the centroids of the clusters, represents the objective:

$$FO(t_i, K) = \sum_{k=1}^{K} \sum_{i=1}^{N_{Tr}} D(t_i, c_k) \quad (1)$$

where K – the number of the clusters, chosen initially by the DM, t_i – the row i from the matrix $[T]_{2xN_{Tr}}$; N_{Tr} – the number of the rows represented by the transformers subject to the clustering process; c_k – the centroid of the cluster k, $k = 1, \ldots, K$; $D(t_i, c_k)$ – the Euclidean distance between each element t_i from matrix $[T]$ and the centroid c_k.

Fig. 6 presents the steps used in the clustering process by the K-means algorithm (Fränti and Sieranoja, 2019; Sinaga, 2020).

The K-means algorithm runs for each partition k, $k = 1, ..., K_{max}$, where K_{max} represents the maximum number of the clusters in which the database can be divided to identify the optimal partition. The relation used in determining the value of K_{max} is the following (Grigoraş *et al.*, 2016):

$$K_{\max} = \sqrt{N_{Tr}} \quad (2)$$

where N_{Tr} represents the number of rows associated with the transformers from matrix $[T]$.

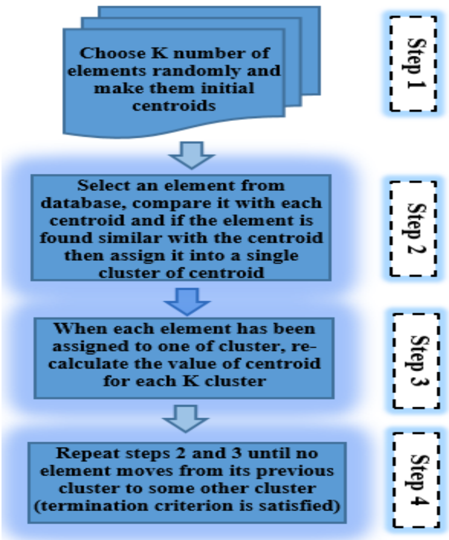


Fig. 6 – The steps of the K-means clustering algorithm.

The optimal partition, K_{opt}, is determined using a quality intern test that uses the silhouette coefficient (SC) as a performance indicator (Rousseeuw, 1987; Wang *et al*., 2017).

$$SC = \frac{v(t_i^k) - w(t_i^k)}{\max\{v(t_i^k), w(t_i^k)\}} \tag{3}$$

where: SC – the silhouette coefficient; $v(t_i^k)$ – the average distance between the element t_i^k, $i = 1, \ldots, N_{Tr}$, and all elements from the same cluster k, $k = 1,\ldots, K$; $w(t_i^k)$ – the average distance between the element t_i^k and all elements assigned to the closest cluster.

The obtained clusters, which corresponds to the optimal partition K_{opt}, are identified in the replacement process with categories having different priority degrees (*Minimum*, *Medium*, and *Maximum*), which influences the replacement order of transformers. The Decision Maker (DM) assigns the priority degree *Maximum* to those categories containing the under or overloading transformers and commissioning years until a reference year, corresponding to the weaker performance standards (higher losses). In the second stage, the replacement ranking of transformers is established based on the solution resulted from a multi-criteria optimization considering the energy-saving and power reserve. Correlation of this solution with the proper classification of transformers in the categories with different priority degrees leads to the formulation of a feasible Decision-Making strategy with economic and technical benefits for the DNO.

The mathematical optimization model has the following components:

Objectives

- Energy-Saving

$$ES(S_r^{(n)}) = \Delta W^{(o)}(S_r^{(o)}) - \Delta W^{(n)}(S_r^{(n)}) \tag{4}$$

$$\Delta W^{(o)}\left(S_r^{(o)}\right) = \Delta P_0^{(o)} \cdot T_f + \Delta P_k^{(o)} \cdot \left(\frac{S_{\max}}{S_r^{(o)}}\right)^2 \cdot \tau \cdot T_f \tag{5}$$

$$\Delta W^{(n)}(S_r^{(n)}) = \Delta P_0^{(n)} \cdot T_f + \Delta P_k^{(n)} \cdot \left(\frac{S_{\max}}{S_r^{(n)}}\right)^2 \cdot \tau \cdot T_f \tag{6}$$

where: o – the old transformer; n – the new transformer; $\Delta W^{(o)}$, $\Delta W^{(n)}$ – the total energy losses corresponding to the old and new transformer; $S_r^{(n)}$ – the optimal rated power of new transformer; $S_r^{(o)}$ – the rated power corresponding to the old transformer; $\Delta P_0^{(o)}$, $\Delta P_0^{(n)}$ – the non-load losses corresponding to the old and new transformer; $\Delta P_k^{(o)}$, $\Delta P_k^{(n)}$ – the load losses corresponding to the old and new transformer; S_{max} – the apparent power recorded on the low voltage (LV) side of the transformer, recorded at the peak load; τ – the loss factor; T_f – the operating time [hours/year], generally 8760 hours. The "old" term is used for the transformer chosen to be replaced.

The loss factor, τ, is calculated based on the hourly values of the total current measured on the LV side of the transformer, in the electric distribution substation, and recorded in the database of the current and voltage measurements (CVM) of the DNO (ANRE, 2016a).

$$\tau = \frac{\int_0^T I^2 dt}{I_{\max}^2} \tag{7}$$

where T – the analysed period.

- *Power Reserve*

The objective will be quantified through the following relation, depending on the apparent power recorded on the LV side of the transformer, recorded at the peak load, $S_{\max}$:

$$PR(S_r^{(n)}) = S_r^{(n)} - S_{\max} \tag{8}$$

A higher performance standard leads to a smaller value of optimal loading for the new transformer, implying an increase in the power reserve.

The two objectives are not conflicting, such that the multi-criteria problem can be treated as a single objective problem. Thus, the objective function associated with each transformer t_i, i = 1, …, N_{Tr}, from each replacement category k, k =1, …, K_{opt}, ordered according to the priority degree, has the following expression:

$$FO_{t_i}^{(k)}(S_{r,opt}^{(n)}) = \max\{FO_{t_i}^{(k)}(S_r^{(n)})\} = \max_{S_r^{(n)}\in\{S\}}\left\{\alpha_1 \cdot \frac{ESt_{t_i}^{(k)}\left(S_r^{(n)}\right)}{\Delta W_{t_i}^{(k)}\left(S_r^{(o)}\right)} + \alpha_{2.} \cdot \frac{PR_{t_i}^{(k)}\left(S_r^{(n)}\right)}{PR_{t_i}^{(k)}\left(S_r^{(o)}\right)}\right\} \tag{9}$$

$$\alpha_1 + \alpha_2 = 1 \tag{10}$$

where: α_1 and α_2 – the weights of each objective assigned by the DM in the replacement strategy; $PR(S^{(o)}{}_r)$ – the power reserve of the old transformer calculated with the rated power $S^{(o)}{}_r$; k – the replacement category; $\{S\}$ – the set of rated powers {50 kVA, 100 kVA, 160 kVA, 250 kVA, 400 kVA, 630 kVA}; $S^{(n)}{}_{r,\ opt}$ – the value of the rated power for which the objective function has the maximum value.

Constraints

- *The loading of the new transformer at the peak load:*

$$0.9 \cdot S_{opt}^{(n)} \le S_{\max} \le 1.1 \cdot S_{opt}^{(n)} \tag{11}$$

where: $S^{(n)}_{opt}$ – the optimal loading of the new transformer given by the manufacturer. The loading of the new transformer must be between 0.9 and 1.1 from the optimal loading.

- *The energy losses*:

$$\Delta W(S_{r,opt}^{(n)}) < \Delta W(S_r^{(o)}) \tag{12}$$

The energy losses of the new transformer must be smaller than those of the old transformer.

4. Case Study

The proposed strategy has been applied for a transformers fleet with 114 MV/LV units belonging to a DNO from Romania.

The transformers exceeding the lifetime (outdated performance standards) and the over or under loading at the peak load have been assigned the highest priority degree (*Maximum*). The "Tier 1" performance standard will be considered for the new transformers.

Thus, the input data represented by the transited power (S_{max}) at the peak load and the commissioning year (*CY*) for each transformer were prepared and uploaded in the matrix [*T*]. The K-means algorithm ran for each partition k, k = 1, ..., K_{max}, where K_{max} = 10 (the value was determined with relation (2)).

The quality of each partition, k, k = 2, …, K_{max}, was evaluated based on the silhouette coefficient. The optimal solution corresponds to a grouping in 5 clusters obtained for the maximum value of the global silhouette coefficient, see Fig. 7.

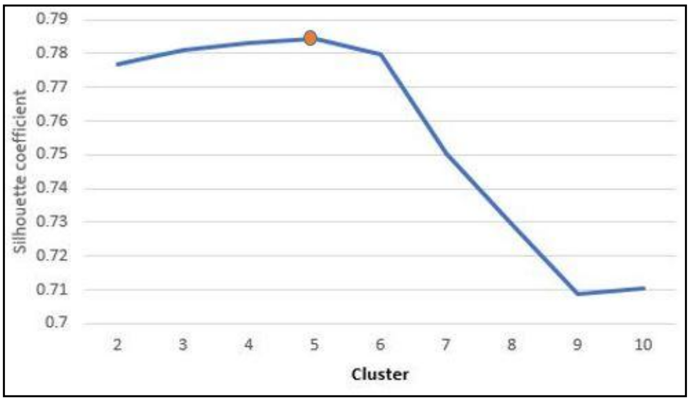


Fig. 7 – The global silhouette coefficient for all considered partitions, k = 1, …, 10.

The quality of the clustering process, in the optimal case, can be observed in Fig. 8, where each cluster, further referred to as a category, is very well defined.

Fig. 9 presents the 2-D representation of the elements (transformers) assigned to each category with the allocation of the priority degree in the replacement process. Table 2 includes the details on the characteristics represented by the statistical indicators, mean (m) and standard deviation (σ), for each category.

The priority degrees (*Maximum*, *Medium*, and *Minimum*) have been assigned to these categories in the Decision-Making Process, influencing the replacement order of transformers. The *Maximum* priority degree will be attached to the categories with weaker performance standards (higher losses) and the over and under loading of the transformers. An ordering, considering the priority degrees, can be established for a replacement direction from left to right: C5, C1, C4, C2, and C3, see Fig. 9.

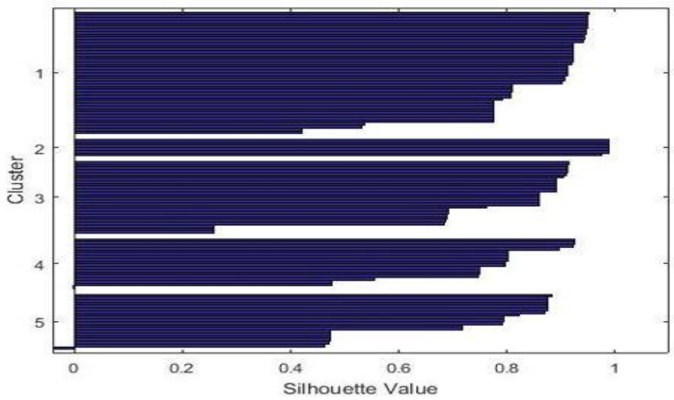


Fig. 8 – The value of the SC inside of each cluster for K_{opt} = 5.

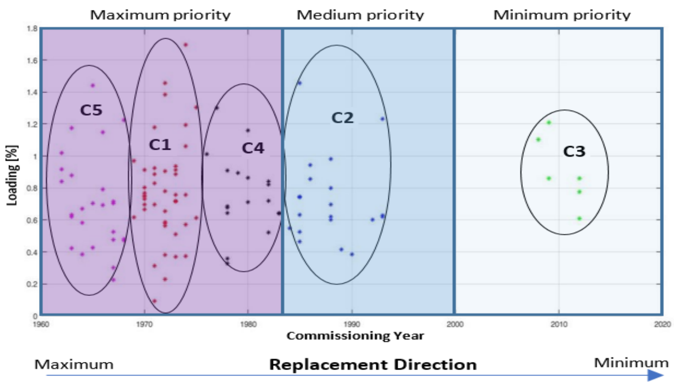


Fig. 9 – The 2-D representation of clusters (K_{opt} = 5) with the priority degree.

Table 2
The Characterization of Categories by Statistical Indicators of the Variables Used in the Replacement Process

Category	Priority degree	Number of transformers	YC		S_{max} [%]		S_r [kVA]	
			m	σ	m	σ	m	σ
C1	Maximum	44	1972	1.58	0.77	0.32	161	86
C2	Medium	20	1988	3.02	0.72	0.27	184	91
C3	Minimum	6	2010	1.86	0.90	0.22	128	67
C4	Maximum	18	1980	2.20	0.76	0.25	144	72
C5	Maximum	26	1965	2.04	0.71	0.30	161	63

The replacement order of transformers from each category is established based on a multi-criteria optimization process in the second stage. The equal weights (α_1 = α_2 = 0.5) for both objectives, the energy-saving and power reserve, were considered in the study. Any combination between α_1 and α2, subject to relation (7), can be chosen by the DM considering the characteristics of each supply area.

Figs. 10 and 11 indicate a comparison between maximum loadings and the rated powers of each transformer assigned to each category before and after the replacement process.

The analysis of the obtained results from Table 3 indicates a decrease in the mean of the maximum loading between 0.45 and 0.48, except for the last category, C3, which has a slightly higher value (0.53). The standard deviation is smaller, offering a high confidence degree in the mean. The rated power increased for the equivalent transformer, from 160 kVA, see Table 3, to 250 kVA equivalent.

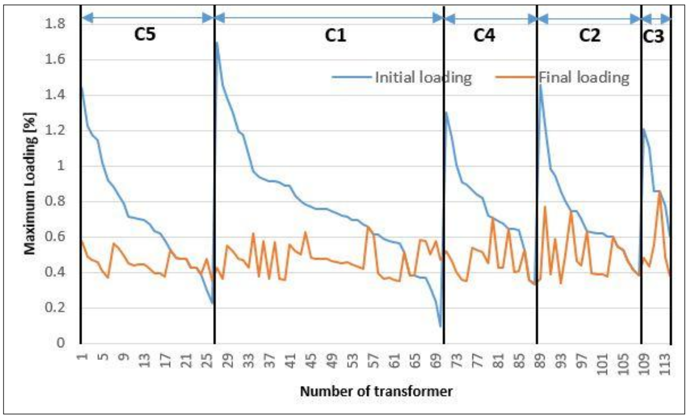


Fig. 10 – The initial and final maximum loading of the transformers.

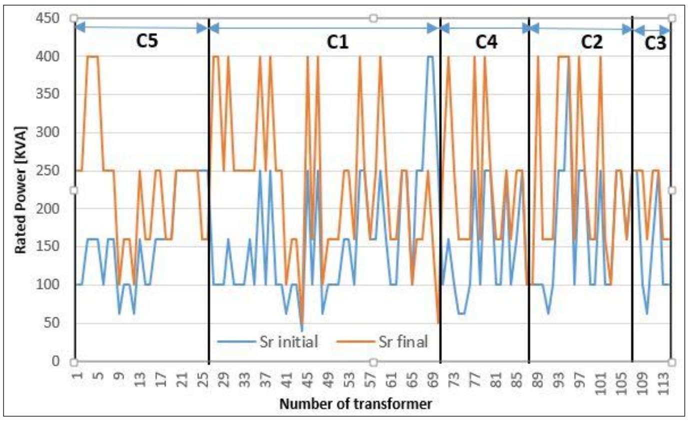


Fig. 11 – The rated power of the transformers ordered after maximum loading.

Table 3
The Statistical Indicators of the Characteristics Associated the Priority Category After the Optimization Process

Clusters	Priority degree	S_{max} [p.u.]		S_r [kVA]	
		m	σ	m	σ
C5	Maximum	0.45	0.06	228	81
C1	Maximum	0.47	0.09	235	102
C4	Maximum	0.46	0.10	223	96
C2	Medium	0.48	0.13	263	134
C3	Minimum	0.53	0.17	205	49

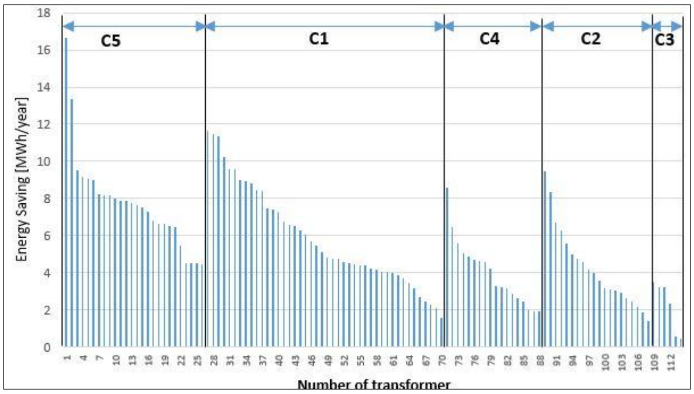


Fig. 12 – The replacement ranking of the proposed strategy with highlighting the energy-savings.

Fig. 12 presents the replacement ranking of the proposed strategy considering the priority degrees assigned to each category, highlighting the energy-savings. If the commissioning years overlap and belong to the same performance standard (the cases C5 and C1, or C4 and C2), the categories can be merged, the replacement order being modified.

Finally, the performance indicators are evaluated, see Table 4, and the values are compared with other strategies proposed in the various studies, see Table 5. The analysis of the obtained performance indicators demonstrated the efficiency of the proposed strategy related to the energy-saving (ES), 0.68 GWh/year and 6.1 MWh/year/transformer, and the average power reserve (PR_{av}), 53.1%, see Table 4.

The strategy S1 corresponds to the same rated power of the transformers (Mihai *et al*., 2010), and S2 (Grigoraș *et. al*., 2017) considers only the energy-efficiency criterion (α_1 = 1), without the power reserve criterion (α_2 = 0). The comparison between the three strategies highlighted the following observations:

- The highest power reserve corresponds to S3, with 27.4% over S1 and 13.6% over S2;
- The total energy-saving obtained in S2 is very close with those from S3, (only 10 MWh/year) and much higher than S1 (190 MWh/year);
- The energy-saving per transformer between the last two strategies is very small (0.2 MWh/year/transformer) and higher than strategy S1.

These results strengthened, again, the efficiency of the proposed strategy compared with the others applied until now by the DNOs.

Table 4
The Performance Indicators of The Proposed Strategy

Clusters	Priority degree	Number of transformers	PR_{av} [%]	ES_{Total} [MWh/ year]	ES_{TR} [MWh/ year/ tr]
C5	Maximum	26	54.8	245.9	9.5
C1	Maximum	44	52.7	260.6	5.9
C4	Maximum	18	53.6	72.2	4.0
C2	Medium	20	51.5	85.3	4.3
C3	Minimum	6	46.7	13.4	2.2
Total		114	53.1	677	6.1

Table 5
Comparison Between the Various Strategies

Strategy	PR_{av} [%]	ES_{Total} [MWh/ year]	ES_{TR} [MWh/ year/ tr]
S1 (keeping same rated power)	25.4	486	4.5
S2 (α_1 = 1, α_2 = 0)	39.2	687	5.96
S3 (α_1 = 0.5, α_2 = 0.5) - proposed	53.1	677	5.93

5. Conclusions

In the paper, the replacement process of the distribution transformers with outdated performance standards and exceed lifetimes has been treated. In this context, a decision-making strategy based on two stages has been proposed and tested for a transformer fleet with 114 units belonging to a DNO from Romania. In the first stage, a K-means clustering-based classification of the transformers has been done. A priority degree (*Maximum*, *Medium*, and *Minimum*) has been assigned to each category obtained in the clustering process depending on the loading level and commissioning year. Only four clusters corresponded to the Maximum (C5, C1, and C4) and Medium (C2) priority degrees, showing a high interest in the replacement process. The category C3 represented a minimum interest, ranking last in the replacement preference. In the second stage, a multi-criteria analysis is applied to identify the optimal solution for each transformer. The considered objectives were energy-saving and power reserve. As the final solution, a replacement ranking considered a descending order from the high to low the energy-saving, for each category, has been finalized. Based on the optimization process, the new transformers have a maximum loading between 0.45 and 0.48. It represents an advantage for the DNO in terms of the power reserve available in the transformers, mainly in the areas where connection requests from new consumers. The rated power increased for the equivalent transformer, from 160 kVA to 250 kVA equivalent. The obtained results lead to a total energy saving by 0.68 GWh/year and a specific energy-saving by 6.1 MWh/year/transformer.

Only the technical aspect of the replacement problem has been analysed for the proposed strategy, demonstrating its feasibility. The proposed approach can offer feasible solutions when the Decision-Maker knows very well each supply area to establish the weight of each objective. Therefore, an inadequate decision could lead to the solutions which to influence negative investments.

Integration of the economic and environmental impacts represents the following objectives of the authors in the future work.

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STRATEGIE DE LUARE A DECIZIILOR BAZATĂ PE O ANALIZĂ MULTI-CRITERIALĂ PENTRU ÎNLOCUIREA TRANSFORMATOARELOR ÎN REȚELELE ELECTRICE DE DISTRIBUȚIE

(Rezumat)

În lucrare, se propune o strategie îmbunătățită bazată pe o analiză multicriterială, care conține două etape de luare a deciziilor, pentru a ajuta Operatorii de Distribuție în procesul de înlocuire a transformatoarelor vechi (cu durate de viață și standarde pe performanță depășite). În prima etapă se folosește algoritmul de clustering K-Medii pentru clasificarea în categorii de importanță în procesul de înlocuire a transformatoarelor, cărora le sunt atribuite grade de prioritate în funcție de încărcarea maximă și anul punerii în funcțiune. În etapa a doua se stabilește un clasament de înlocuire întocmit pe baza unei analize multicriteriale, având în vedere economia de energie și rezerva de putere disponibilă în transformator. O bază de date formată din 114 transformatoare a fost folosită pentru a demonstra eficiența strategiei propuse. Rezultatele obținute au evidențiat o creștere a rezervei de energie cu 27% și economia de energie cu 39%, comparativ cu situația inițială.