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Weight Optimization of Oil Type Transformer with Crayfish Optimization Algorithm

Emine BAŞ[1] and Lütfi Batuhan GÜNER[1]

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Research Article

Corresponding Author
Lütfi Batuhan GÜNER
e228229052002@ktun.edu.tr

ORCID of the Authors
E.B: 0000-0003-4322-6010
L.B.G: 0009-0002-2935-7495

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Abstract

Transformers used in the transmission and distribution of electricity are electrical machines that ensure the transmission of electricity at constant power and frequency by using magnetic field strength. In this study, weight optimization of oil-type power and distribution-type transformers in different power levels (50kVA and 100kVA) was calculated using the Crayfish Optimization Algorithm (COA). The purpose of the study is to perform weight optimization and calculate weight reduction. The variable parameters used as current density value (s) and iron section suitability value (C) were determined and weight optimization was calculated. A detailed population size analysis (for ten different population values) and maximum iteration analysis (for four different maximum iteration values) were performed on the weight optimization problem of transformers with COA. The effects of changing population sizes and maximum iteration numbers on the performance of COA were shown. The results obtained were analyzed in detail by comparing them with other studies in the literature (GWO, FA, OOA, and ZOA). While the transformer iron weight calculated with the traditional approach with COA is further minimized, the efficiency is further maximized. When the comparison results are examined for 50kVA and 100kVA, while COA increases the efficiency of transformers better than old heuristic methods such as GWO and FA, it could not minimize the iron weight. It was also observed that the C and s variable values were similar in all three algorithms (COA, GWO, and FA). When the COA, ZOA, and OOA algorithm results are examined for 50kVA and 100kVA, the heuristic algorithm that finds the minimum total iron weights is COA, while the highest efficiency is again achieved by COA. COA's transformer total iron weight results were consistent with the traditional, ZOA and OOA algorithms, but not with GWO and FA. In addition, the transformer efficiency calculated depending on the iron weight showed the best performance with COA among the comparison algorithms. This study has shown that transformer weight can be reduced and efficiency can be increased by using intuitive methods. The solution to the transformer iron weight calculation problem with COA is a first in the literature and the obtained results were introduced to the literature.

Keywords: Transformer, crayfish optimization algorithm, efficiency, transformer weight optimizatio

Kerevit Optimizasyon Algoritması ile Yağlı Tip Transformatörün Ağırlık Optimizasyonu

[1]Konya Technical University, Faculty of Engineering and Nature Sciences, Department of Software Engineering, Konya, Türkiye

Öz

Elektriğin iletim ve dağıtımında kullanılan transformatörler, manyetik alan kuvvetini kullanarak elektriğin sabit güç ve frekansta iletilmesini sağlayan elektrikli makinelerdir. Bu çalışmada farklı güç seviyelerindeki (50kVA ve 100kVA) yağlı tip güç ve dağıtım tipi transformatörün ağırlık optimizasyonu Kerevit Optimizasyon Algoritması (COA) kullanılarak hesaplanmıştır. Çalışmanın amacı ağırlık optimizasyonu yapmak ve ağırlık azaltımını hesaplamaktır. Akım yoğunluk değeri (s) ve demir kesit uygunluk değeri (C) olarak kullanılan değişken parametreler belirlenerek ağırlık optimizasyonu hesaplanmıştır. COA'lı transformatörlerin ağırlık optimizasyon problemi üzerinde detaylı bir popülasyon büyüklüğü analizi (on farklı popülasyon değeri için) ve maksimum iterasyon analizi (dört farklı maksimum iterasyon değeri için) gerçekleştirilmiştir. Değişen popülasyon büyüklüklerinin ve maksimum iterasyon sayısının COA'nın performansına olan etkileri gösterilmiştir. Elde edilen sonuçlar literatürdeki diğer çalışmalarla (GWO, FA, OOA ve ZOA) karşılaştırılarak detaylı bir şekilde analiz edilmiştir. COA ile geleneksel yaklaşımla hesaplanan transformatör demir ağırlığı daha da minimize edilirken verimlilik daha da maksimize edilmektedir. 50kVA ve 100kVA için karşılaştırma sonuçları incelendiğinde COA, GWO ve FA gibi eski sezgisel yöntemlerden daha iyi transformatör verimliliğini artırırken demir ağırlığını minimize edememiştir. Ayrıca her üç algoritmada (COA, GWO ve FA) C ve s değişkeni değerlerinin benzer olduğu görülmüştür. COA, ZOA ve OOA algoritmalarının sonuçları 50kVA ve 100kVA için incelendiğinde, en düşük toplam demir ağırlıklarını bulan sezgisel algoritma COA olurken, en yüksek verimlilik yine COA ile elde edilmiştir. COA'nın transformatör toplam demir ağırlığı sonuçları geleneksel, ZOA ve OOA algoritmalarıyla tutarlıdır, ancak GWO ve FA ile tutarlı değildir. Ayrıca, demir ağırlığına bağlı olarak hesaplanan transformatör verimliliği karşılaştırma algoritmaları arasında COA ile en iyi performansı göstermiştir. Bu çalışma, sezgisel yöntemler kullanılarak transformatör ağırlığının azaltılabileceğini ve verimliliğin artırılabileceğini göstermiştir. Transformatör demir ağırlığı hesaplama probleminin COA ile çözümü literatürde bir ilktir ve elde edilen sonuçlar literatüre kazandırılmıştır.

Anahtar Kelimeler: Transformatör, kerevit optimizasyon algoritması, verimlilik, transformatör ağırlık optimizasyonu

Introduction

With the advancement of science and technology, solving problems quickly and in the best way has become even more important. Optimization processes are performed to find the fastest and best solution. Optimization provides the optimal solution by imposing certain constraints on the solution of the given problem. It accelerates the process and provides accurate and best results in solving problems in many areas of optimization and decision-making in the field of engineering. Many scientists have developed optimization algorithms, techniques, and methods on this subject [1]. Heuristic research methods emerged because classical methods were not sufficient in terms of finding the solution to real-life problems, finding the best result, and increasing the complexity of the problem as the size of the problem increases. Meta-heuristic algorithms provide more diverse results regarding convergence, global optimum, and local optimum than traditional algorithms and are also used in solving continuous or discrete (binary) problems [1]. Meta-heuristic algorithms are considered as swarm intelligence, evolutionary algorithms, physics-based algorithms, and human-inspired algorithms and also they are mostly inspired by nature. Artificial Bee Algorithm (ABC) [2], Harris Hawk Optimization (HHO) [3], Wild Horse Optimization (WHO) [4], Particle Swarm Optimization (PSO) [5], Ant Colony Optimization (ACO) [6] and Crayfish Optimization Algorithm (COA) [7] can be given as examples of swarm intelligence algorithms. Electromagnetic Field Optimization [8], Gravitational Search Algorithm [9], and Simulated Algorithm [10] can be given as examples of physics-based algorithms. Genetic algorithms can be given as examples of evolutionary algorithms [11, 12]. Electrical energy at constant power and constant frequency, conduction by increasing/decreasing the voltage level special type of electrical equipment called a power transformer machines are used. Electrical energy has a very important place in transmission and distribution. Transformers according to their intended use; converter or amplifier according to the number of phases; depending on the type of cooling, it can be classified as single or multi-phase, dry or oily. The optimization process of electrical machines is difficult in the transmission and distribution of electrical energy it started with the widespread use of distribution transformers. Transformers are divided into two types, dry and oiled, according to the cooling insulation material of the windings. Dry-type transformers have a higher upfront cost than oil-type transformers [13]. In general, oil-type transformers tend to have higher efficiency compared to dry-type transformers. The higher efficiency of oil-type transformers means they have lower losses, resulting in less energy consumption and lower operating costs in the long run [14]. Looking at the discoveries added to the literature, different optimization techniques and different algorithms have been used in the field of electrical machines. How to increase the energy efficiency in power distribution of Amorphous Metal Core Distribution Transformers (AMDT) has been calculated using artificial intelligence optimization. AMDT has the potential to reduce transformer no-load losses by up to 70% compared to conventional technology. Carlen et al. [15] discussed general aspects of AMDT transformer losses, both liquid-filled and dry type, and their impact on the total cost of ownership. Various case studies of economic and environmental benefits are presented. Applications where the use of AMDT is most beneficial, such as renewable energy production, are also presented. AMDT offers a sustainable approach when capitalized losses and environmental impacts are taken into account [15]. Çelebi was made the cost optimization of the 100kVA oil-type transformer, which was previously designed using analytical methods, using a Genetic Algorithm [16]. It is aimed to reduce the cost by taking the weight of the transformer as a criterion. According to the results obtained, a weight reduction of approximately 10% was observed [16]. In another work by Celebi, the weight of a dry-type transformer with an apparent power of 1.5kVA was tried to be optimized using the Genetic Algorithm [17]. The boundary variables in the optimization process were determined as the current density (s) value and the iron section suitability (C) value, and it was observed that the weight decreased by 20% within these limits [17]. The transformer is 50 kVA oil type transformer weight optimization was performed with the Firefly Algorithm by Akdağ and Çelebi [18]. 50 kVA oil-type transformer weight optimization is simulated [18]. This study is carried out by optimizing the current density (s) and iron cross-section compliance factor (C) of the transformer. It is aimed to reduce the weight of the transformer and the cost depending on the weight to the optimal level. There was a decrease of 11% in weight approximately [18]. The efficiency of a dry-type transformer with 100 kVA apparent power was tried to be maximized using the Firefly algorithm by Demirdelen [19]. The transformer was designed by optimizing it according to iron cross-section suitability (C) and current density (s) values, and 97% efficiency was achieved [19]. The weight and efficiency of the 1.5kVA dry-type transformer were optimized using the Taboo Search Algorithm by Tosun et al. [20]. Limit values are determined as current density value and iron section suitability value. As a result of the study, the transformer weight was calculated as 23.55 kg and the efficiency was calculated as 92.3%. The results found are compared to classical methods, resulting in less core and iron loss, resulting in lower energy and cost savings. It has been observed that they provide savings [20]. In another study power and distribution type transformers weight optimization was calculated were analyzed by using the Gray Wolf Optimization Algorithm by Toren and Mollahasanoğlu [21] in 2023. Boundary values are determined as current density (s) value and iron cross-section suitability (C) value. As a result of the study, the weight of 50 kVA, 100 kVA, and 1000 kVA transformers is transformer weights are reduced by respectively 31%, 21%, and 9%, and transformer costs due to weight have been observed that it can reduce [21]. In another study, oil was used as cooling insulation material in oil-type transformers by Senthilkumar et al. [22] in 2021. The aim of the study is to increase its efficiency depending on the oil used. In the study, different oils were mixed with each other in certain proportions, and optimum liquid isolation was achieved using GRA (Grey Relationship Analysis). As a result of the study, the mixing ratio of mineral oil and sunflower oil was determined as 10:90 and it was observed that it showed higher performance than other samples and it was concluded that Gray Relational Analysis (GRA) is a possible solution. Method for determining the optimum sample concentration of mixed liquid insulation [22]. In another study, the equivalent circuit drawing was designed by determining the best voltage value of both single-phase and 3-phase transformers using the Coyote Optimization Algorithm by Abdelwanis et al. [23] in 2020. Parameter estimates of the transformers were made with the Jaya Optimization Algorithm and Particle Swarm Optimization [23]. In addition to these studies, the weight of the main materials of the transformer was estimated with the Fuzzy Logic Method, and as a result of these estimates, it was made easier for public services to use their capital efficiently, to make the transformer life longer and to estimate it for the use of manufacturers by Malik and Jarial [24] in 2011. Pramono et al. [25] conducted a study on the design of a power transformer using Particle Swarm Optimization (PSO), focusing on transformer noise, weight, and losses. The PSO algorithm was utilized in the study to achieve the main objective of developing a power transformer with low noise and low cost. The objective function aimed to minimize load noise, core weight, and winding weight. The optimization results showed reductions of 0.86 dB in load noise, 2.12% in core weight, and 47.46% in winding weight, respectively. These results are superior to the designs commonly used in the industry [25]. Hashemi et al. [26] represented a study on the applications of new heuristic algorithms in the design optimization of energy-efficient distribution transformers. The study presents an optimization method for the transformer design problem by using variables that have a significant impact on transformer performance. Considering the No Free Lunch (NFL) theorem, the design problem was solved using four novel heuristic optimization algorithms: the Firefly Optimization Algorithm (FA), the Arithmetic Optimization Algorithm (AOA), the Grey Wolf Optimization Algorithm (GWO), and the Artificial Gorilla Troops Optimizer Algorithm (GTO). The results were compared with a 1000 kVA environmentally friendly distribution transformer that was already produced using empirical methods. As a result of the optimization, the proposed method, in conjunction with the mentioned algorithms, led to a noticeable reduction of up to 3.5% in power losses and up to 8.3% in transformer weight. This improvement results in increased efficiency, reduced material costs, longer service life, and lower emissions [26]. Another study defines the design and optimization of a Medium Frequency Transformer. Additionally, design filters have been developed to enable the search for the most preferred design alternatives in terms of hotspot temperatures, weight, volume, and efficiency [27]. Garcia-Bediaga et al. [28] proposed a study on the multi-objective optimization of Medium Frequency Transformers for Isolated Soft-Switching Converters using Genetic Algorithms. The main objectives are to optimize transformer efficiency, weight, leakage inductance, and magnetizing inductance. The study evaluates 10-kVA/500-V transformers based on two different topologies. In conclusion, some experimental measurements are presented to demonstrate the performance of the proposed models and the constructed transformers. Zhang et al. [29] presented a study on the optimization design of a high-power, high-frequency transformer based on a Multi-Objective Genetic Algorithm. The study focuses on transformer optimization under constrained conditions, including transformer losses, insulation, and leakage. Using the NSGA-II algorithm, a transformer prototype with specifications of 220V/3.52kV, and 3.52kW/20kHz was produced. In another study, the variables to be optimized were identified as core loss, leakage inductance, overall losses, and efficiency. Experimental results confirmed the consistency of the calculations and validated the acceptability of the optimization method studied. Another study is the weight optimization of a core-form oil-filled transformer using heuristic search algorithms. In another study, a 100 kVA oil-type transformer is selected. The heuristic algorithms used in the study include methods such as Particle Swarm Optimization (PSO), Simulated Annealing (SA), and Gravitational Search Algorithm (GSA). The results are compared with the classical method. In the Heuristic Search Algorithms method, the total weight of the transformer is taken as the objective function. Efficiency (η) and (Ls/a) are taken as constraints. The total weight determined using Heuristic Search Algorithms is less than the weight determined by the classical method [30]. In this study, a real-world problem is solved. In this problem, transformer current density (s) and iron section compatibility (C) constraints are discussed. These two variables affect the total iron weight of transformers. The total iron weight affects the efficiency of transformers. The problem aims to calculate the minimum iron total depending on the *s* and *C* variables to increase the efficiency of transformers. The values of total iron weight, efficiency, *s,* and *C* variables are calculated by traditional methods in the literature. There are existing traditional method results. When the literature is examined, the efficiency of transformers is also increased by using heuristic algorithms. Genetic Algorithm (GA) [16, 17], Firefly Algorithm (FA) [18, 19], Tabu Search Algorithm (TS) [20], Gray Wolf Optimization (GWO) [21], and Coyote Optimization Algorithm (COA) [23] are meta-heuristic algorithms in the literature and are used to optimize the transformer weight. When the literature results are examined, *C* and *s* variables are calculated with heuristic algorithms, and minimum total iron weights and maximum efficiency are found. In this study, the Crayfish optimization algorithm (COA) is examined. The COA is one of the newly proposed heuristic algorithms in recent years. COA was proposed by Jia et al. [7] in 2023. COA is a meta-heuristic algorithm created by imitating the feeding and lifestyles of crayfish in the exploration and exploitation stages in a continuous search space. The success of a heuristic algorithm is the degree to which it balances the abilities to explore and exploit the search space. Although the COA algorithm has been tested on many different engineering design problems, its success in solving transformer design optimization has not been shown. In the literature, newly proposed heuristic algorithms prove their success on classical benchmarks and various engineering design problems. However, this success does not always continue on different problems. Therefore, it is necessary to prove the success of newly proposed heuristic algorithms on various types of problems. The use of heuristic algorithms that have been proven to be successful in different types is increasing in the literature by different researchers. The main focus of this study lies here. According to the literature review, it was seen that transformer optimization has not been done with COA before. In this study, it is aimed to minimize the total weight of transformers and maximize their efficiency by using COA. The study was carried out considering 3-phase, star/delta, frequency 50 Hz, star/delta connected, 50 kVA, and 100 kVA oil-immersed transformers. The mathematical model of the designed transformer is available in the literature. It was created based on transformer studies taken from [16, 18]. The originality of this study is that COA has not been used in transformer design and transformer weight optimization studies in the literature before. The obtained results are competitive with the literature and have increased the usability of COA in different real-world problems.

The main contributions of this study:

a-) The total iron weight of a transformer with the COA heuristic algorithm has been carried out for the first time depending on the variables s and C. The results have been added to the literature.

b-) The balance established by COA between exploration and exploitation in the search space has also been shown on a different problem in this study.

c-) A detailed population size and maximum iteration parameter analysis have been performed in transformer optimization.

d-) To compare the results of COA, the transformer optimization problem has been solved with the OOA and ZOA algorithms that have been newly proposed in the literature in recent years and the results have been compared with each other. The results of the Osprey Optimization Algorithm (OAA) and Zebra Optimization Algorithm (ZOA) algorithms have also been added to the literature.

e-) COA results are much better than the total iron weight and efficiency calculated with traditional methods. In addition, the superiority of COA results is remarkable when compared to ZOA and OOA. When compared to FA and GWO results, the total iron weight result was minimized less in COA, and this did not affect the transformer efficiency. This situation also showed that FA and GWO total iron weight results should be discussed. The remainder of this work is structured as follows: COA and the design of the transformer weight calculation with traditional methods are explained in detail in Section 2. In Section 3, oil-type transformers with 50 kVA and 100 kVA power have been redesigned with COA, and their performances are shown. The obtained performances were then compared with traditional methods, Gray Wolf Optimization (GWO) [21], Firefly Algorithm (FA) [18], Osprey Optimization Algorithm (OAA) [31] Zebra Optimization Algorithm (ZOA) [32]. The total weight values and efficiency values were shown in this study.

Materials and Methods

In this study, different power levels The current label weight of transformers (50kVA and 100kVA) is determined by the traditional calculation method with theoretical data and approaches [16-18]. Boundary variable parameters used in the optimization current density values (s) and iron cross section *(C)* values using the Crayfish Optimization Algorithm (COA) most optimum transformer weight values were calculated [7].

Crayfish Optimization Algorithm (COA)

Recently, Jia et al. [7] have presented a new meta-heuristic optimization algorithm called as Crayfish Optimization Algorithm (COA) to tackle continuous optimization problems and obtain the most efficient results [7]. COA is formulated mathematically as:

Step 1: Initialize Population

In the multi-dimensional optimization problem, each crayfish is a matrix of 1 × dim. Each column matrix represents a solution to a problem. In a set of variables ($X_{i,1}$, $X_{i,2}$, ..., $X_{i,dim}$), each variable X_i must lie between the upper and lower boundaries. The initialization of COA is to randomly generate a group of candidate solutions X in the space. Candidate solution X is based on population size N and dimension dim. The initialization of COA algorithm is shown in Eq. (1) [7].

$$X = X_1, X_2, \dots, X_N = \begin{vmatrix} X_{1,1} & \dots & X_{1,j} & \dots & X_{1,dim} \\ X_{i,1} & \dots & X_{i,j} & \dots & X_{i,dim} \\ X_{N,1} & \dots & X_{N,j} & \dots & X_{N,dim} \end{vmatrix}, \quad (1)$$

where X is the initial population position, N is the number of populations, dim is the population dimension, $X_{i,j}$ is the position of individual i in the j dimension, and $X_{i,j}$ value is obtained from Eq. (2) [7].

$$X_{i,j} = lb_j + (ub_j - lb_j) \times rand, \tag{2}$$

where lb_j represents the lower bound of the j^{th} dimension, ub_j represents the upper bound of the j^{th} dimension and *rand* is a random number [7].

Step 2: Define The Temperature and Intake of Crayfish

Changes in temperature will affect the behavior of crayfish, causing them to behave differently. Temperature is described as Eq. (3). When the temperature is higher than 30 °C, the crayfish will decide or choose a cool place for summer vacation. At a suitable time temperature, crayfish will exhibit foraging behavior. The food consumption amount of crayfish is affected by temperature. The food consumption range of crayfish is between 15, 30, and 25 °C is the best. So, COA defines a range of temperatures from 20 to 35 °C [7].

$$temp = rand \times 15 + 20, \tag{3}$$

where *temp* represents the temperature of the environment where the crayfish is located. The mathematical model of crayfish intake is shown in Eq.(4) [7].

$$p = C_1 \times \left(\frac{1}{\sqrt{2\times\pi\times\sigma}} \times \exp(-\frac{temp - \mu^2}{2a^2})\right), \tag{4}$$

where μ represents the most suitable temperature for crayfish, and σ and C_1 are used to control crayfish intake of crayfish at different temperatures [7].

Step 3: Summer Resort Stage (exploration)

When the temperature is >30 the temperature is too high. At this time crayfish will opt to move on the cave for summer vacation. The X_{shade} cave is described in Eq.(5) [7].

$$X_{shade} = \frac{X_G + X_L}{2}, \tag{5}$$

where X_G represents the optimal position obtained so far based on the number of iterations, and X_L represents the optimal position of the current population. When *rand*<0.5 this means nothing is happening other crayfish are competing for caves, and crayfish will go directly into the cave for summer vacation. Meanwhile, crayfish came to the cave as a summer resort and will enter using Eq.(6) [7].

$$X_{ij}^{t+1} = X_{ij}^t + C_2 \times rand \times (X_{shade} - X_{ij}^t), \tag{6}$$

where *t* represents the current number of iterations and *t+1* represents the next generation the number of iterations, C_2, is a decreasing curve as shown in Eq.(7). *T* represents the maximum number of iterations [7].

$$C_2 = 2 - \frac{t}{T}, \tag{7}$$

Step 4: Competition Stage (exploitation)

$$X_{ij}^{t+1} = X_{ij}^{t} - X_{zj}^{t} + X_{shade}, \tag{8}$$

When *temp*>30 and *rand* ≥0.5, it means other crayfish are also interested in the cave. Meanwhile, they will fight to take the cave. The crayfish competes for the cave through Eq. (8) [7].
where *z* represents the random individual of crayfish as shown in Eq.(9) [7].

$$z = round\big(rand \times (N-1)\big) + 1, \tag{9}$$

Step 5: Foraging Stage (exploitation)

When the temperature is ≤30, the temperature is suitable for crayfish to feed. At this time, the crayfish will move towards the food [7].
The food location X_{food} is in Eq.(10) [7].

$$X_{food} = X_G, \tag{10}$$

Food size Q is in Eq.(11) [7].

$$Q = C_3 \times rand \times \left(\frac{fitness_i}{fitness_{food}}\right), \tag{11}$$

where C_3 is the food factor representing the largest food and its value is constant 3, $fitness_i$ represents the fitness value of the i^{th} crayfish, and $fitness_{food}$ represents the fitness value, and the value of food location [7].
When Q > (C_3+1)/2, it means that the food is too big. At this time, the crayfish will tear the food with the first claw foot. It is in Eq.(12) [7].

$$X_{food} = \exp\left(-\frac{1}{Q}\right) \times X_{food}, \tag{12}$$

The equation for foraging is in Eq. (13) [7].

$$X_{ij}^{t+1} = X_{ij}^{t} + X_{food} \times p \times (\cos(2 \times \pi \times rand) - \sin(2 \times \pi \times rand), \tag{13}$$

When $Q \leq$ (C_3+1)/2, the crayfish must move towards the food and eat it directly, the equation is in Eq.(14) [7].

$$X_{ij}^{t+1} = \left(X_{ij}^{t} - X_{food}\right) \times p + p \times rand \times X_{ij}^{t}, \tag{14}$$

The pseudo-code of COA is presented in Figure 1 [7]. The flow chart of COA is presented in Figure 2 [7].

Algorithm 1: Pseudo-code of COA [7]

Initialization iterations T, population N, dimension *dim*

Randomly generate an initial population.

Calculate the fitness value of the population to get X_g, X_L

While $t<T$

    Defining temperature *temp* by Eq.(3)

    If *temp*>30

        Define cave X_{shade} according to Eq.(5).

        If *rand*<0.5

            Crayfish conducts the summer resort stage according to Eq.(6).

        Else

            Crayfish compete for caves through Eq.(8).

        End

exploration

    Else

        The food intake p and food size Q are obtained by Eq.(4) and Eq.(11).

        If Q>2

            Crayfish shreds food by Eq.(13).

            Crayfish foraging according to Eq.(13).

        Else

            Crayfish foraging according to Eq.(14).

        End

exploitation

    End

    Update fitness values, X_g, X_L

    $t=t+1$

End

Figure 1. *Pseudo-code of COA [7]*

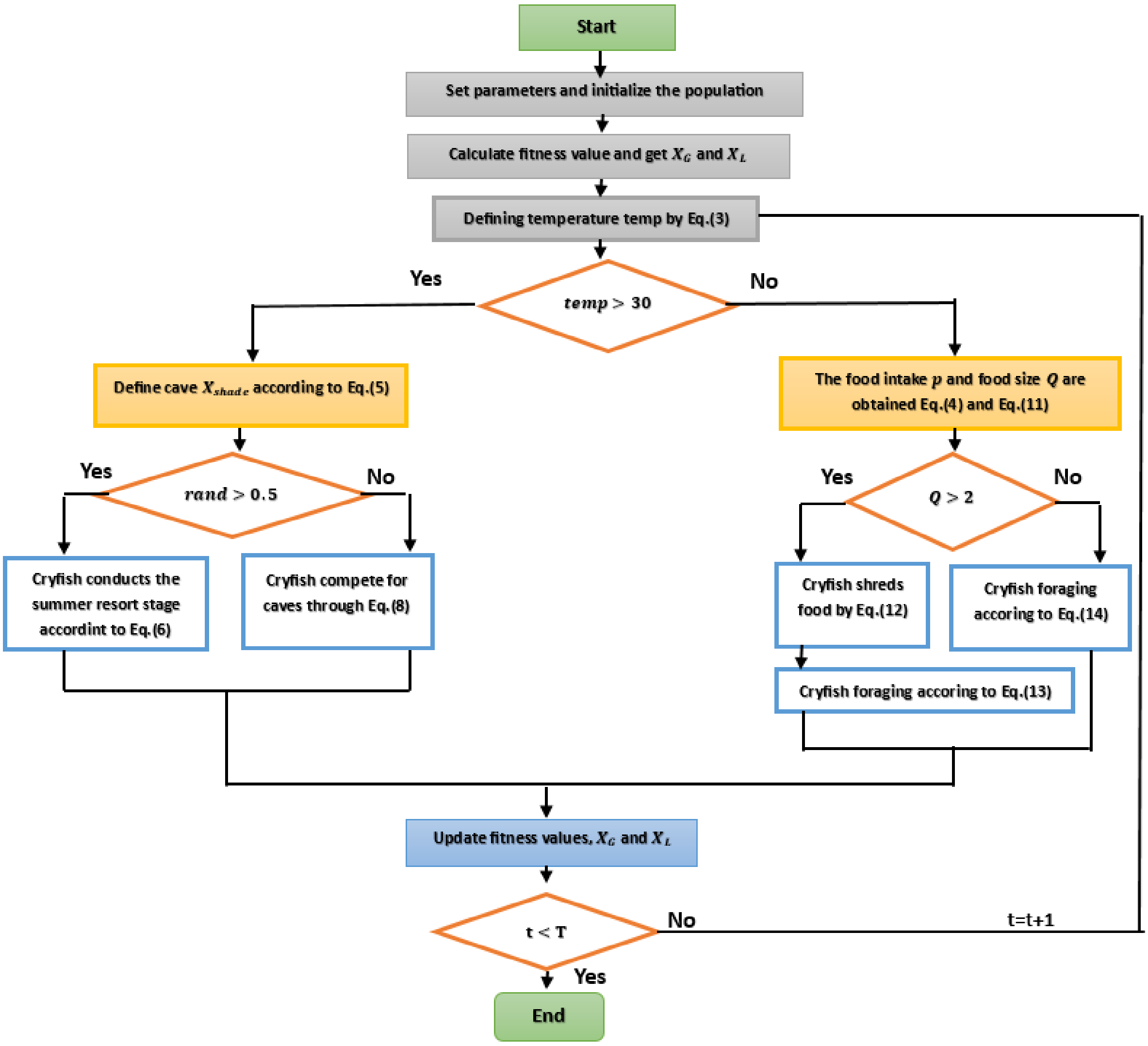

Figure 2. *Flow chart of COA [7]*

The Design of The Transformer Weight Calculation With Traditional Methods

While calculating the weights of transformers in this subsection calculation method is used with formulas and experimental approaches.

Total weight (G_T) is expressed as the sum of iron weight (G_{fe}) and copper weight (G_{cu}) and is given in Eqs. (15-17) [18].

$$G_T = G_{cu} + G_{fe} \tag{15}$$

$$G_{cu} = G_{cu1} + G_{cu2} \tag{16}$$

$$G_{fe} = G_{feb} + G_{fej} \tag{17}$$

where total copper weight, primary winding (G_{cu1}) with the secondary winding of its weight (G_{cu2}) is the sum. G_{fej} and G_{feb} are total iron weights of yoke weight. They can be expressed as the sum weight of each leg. These values are given in Eqs. (18-25) [18].

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$$G_{cu1} = 3 \times 10^{-5} \times \gamma_{cu} \times \omega_1 \times q_1 \times L_{m1}(\text{kg}) \tag{18}$$

$$G_{cu2} = 3 \times 10^{-5} \times \gamma_{cu} \times \omega_2 \times q_2 \times L_{m2}(\text{kg}) \tag{19}$$

$$G_{fe} = 10^{-3} \times \gamma_{fe}(0.3 \times L_s \times q_{fe} \times 2(2M \times 0.8D)q_{fej}(\text{kg}) \tag{20}$$

$$G_{feb} = 3 \times 10^{-3} \times \gamma_{fe} \times q_{fe} \times L_s(\text{kg}) \tag{21}$$

$$G_{fej} = 3 \times 10^{-3} \times \gamma_{fe} \times q_{fe} \times 2(2M + 0.8D)(\text{kg}) \tag{22}$$

$$M = 0.851D + 0.1L_s \tag{23}$$

$$q_1 = \frac{I_1}{s} \tag{24}$$

$$q_2 = \frac{I_2}{s} \tag{25}$$

In the specified equations, ω_1 and ω_2 are the numbers of turns in the upper and lower voltage windings. q_{fe} (cm^2) and q_{fej} (cm^2) are the iron section and yoke leg section, respectively. Also, q_1 and q_2 are first and second winding cross sections, respectively. s is the current density value and the current density value range changes from 2.2-3.5 (A/cm^2) in the oil-type transformers and it changes 1.7-2 (A/cm^2) in the dry-type transformers. γ_{cu} is copper-specific weight. γ_{fe} is the specific gravity of iron. L_{m1} and L_{m2} whereas represents the average upper and lower length of the windings. L_s represents the window or leg height. M variable is given Eq. (23). The core of the transformer and the diameter of the circle are expressed as D [17]. Relevant calculations are shown in Eqs. (26-29) [17, 18].

$$q_{fe} = C\sqrt{\frac{10^3 S}{3f}}\,(cm^2) \tag{26}$$

$$q_{fej} = 1.1\ x\ q_{fe}(cm^2) \tag{27}$$

$$\omega_1 = \frac{U_1}{4.44\sqrt{3}f\theta 10^{-8}} \tag{28}$$

$$\omega_2 = \frac{U_2}{4.44\sqrt{3}f\theta 10^{-8}} \tag{29}$$

Here S is the apparent power, f is the frequency, q_{fe} (cm^2) and q_{fej} (cm^2) respectively, iron section and yoke leg section. C is an iron cross section is the suitability factor. Iron cross-section suitability factor value range is changing in oil type transformers 4 to 6 $(cm^2\ joule^{-1/2})$ and it is changing from 5.9 to 10.6 $(cm^2\ joule^{-1/2})$ in dry-type transformers. ω_1 and ω_2 variables are the number of turns in the upper and lower voltage windings [18].

As shown in Eq. (30) primary winding (G_{cu1}) with the secondary winding of its weight (G_{cu2}) is the sum. The total iron weight of the yoke is the weight (G_{fej}) and (G_{feb}) it can be expressed as the total weight of each leg [18].

$$G_T = G_{cu1} + G_{cu2} + G_{feb} + G_{fej} \tag{30}$$

Finally, the total loss of the transformer (P_k) and accordingly, the efficiency equation is given in Eqs. (31-34) [18].

$$P_{cu} = 2.7 \times s^2 \text{ (Watt/kg)} \tag{31}$$

$$P_{fe} = P_{10} \times \mathcal{E}_2 \times (\frac{\beta}{10000})^2 \text{(Watt/kg)} \tag{32}$$

$$P_k = P_{cu} + P_{fe} \text{(Watt)} \tag{33}$$

$$Efficiency = \frac{S}{S+10^{-3} \times P_k} \tag{34}$$

P_{cu} refers to total copper losses and P_{fe} refers to total iron losses. P_{10} is loss factor, $\mathcal{E}_2$ processing of sheets the additional loss factor resulting from, β is oily type transformer core induction P_k refers to the total loss of the transformer [18].

The most appropriate efficiency is if the copper losses. P_{cu} are equal to the iron losses P_{fe} are transferred to the primary and secondary windings they are reached to be divided equally. The ratio of copper and iron losses is as stated in Eq. (35) [17].

$$\mathcal{E} = \frac{P_{cu}}{P_{fe}} \tag{35}$$

Table 1 shows transformers at different power levels parameter values [21].

Table 1. *Transformers at different power levels have parameter values* [21]

Parameters	Unit	50 kVA	100 kVA
Iron section conformity value (C)	$cm^2\ joule^{-1/2}$	4-6	5-6
Current density value (s)	A/cm^2	2.2	2.6
Number of primary windings	turn	5798	2675
Number of secondary windings	turn	70	31
First winding weight	kg	68.2	63.1
Second winding weight	kg	45.6	46.2
Three feet weight of transformer	kg	105.8	132.5
Yoke weight of transformer	kg	112.8	194.5
Total weight of transformer	kg	332.28	436.3
Efficiency	%	95	92

In Table 1, the iron section conformity value is expressed as C. The measurement unit of C is cm^2 $joule^{-1/2}$. The selection ranges of C for 50 kVA and 100 kVA are [4-6] and [5-6], respectively. In Table 1, the current density value is expressed as s. The measurement unit of s is A/cm^2. The values of s for 50 kVA and 100 kVA are 2.2 and 2.6, respectively. The measurement unit of the numbers of primary and secondary windings is turned. The values of the number of primary windings for 50 kVA and 100 kVA are 5798 and 2675, respectively. The values of the number of secondary windings for 50 kVA and 100 kVA are 70 and 31, respectively. The measurement unit of the first and second winding weight is kg. The values of the first winding weight for 50 kVA and 100 kVA are 68.2 and 63.1, respectively. The values of the second winding weight for 50 kVA and 100 kVA are 45.6 and 46.2, respectively. The measurement unit of the three feet weight of the transformer and the yoke weight of the transformer is kg. The values of the three feet weight of the transformer for 50 kVA and 100 kVA are 105.8 and 132.5, respectively. The values of the yoke weight of the transformer for 50 kVA and 100 kVA are 112.8 and 194.5, respectively. The measurement unit of the total weight of the transformer is kg. Using traditional methods, the total weight of the transformer was found to be 332.28 and 436.3 for 50 kVA and 100 kVA, respectively. The measurement unit of the efficiency is %. Using traditional methods, the efficiency of the transformer was found to be 95 and 92 for 50 kVA and 100 kVA, respectively.

Transformer Weight Calculation with Crayfish Optimization Algorithm

In this study, the Crayfish Optimization Algorithm (COA) is applied using MatlabR2022B software to optimize the weight of transformers at different power levels. With this algorithm, current density (s) and cross-section compatibility factor (C), which are the variable parameters of the iron part of the transformers, are used. The objective function was determined as the total weight of the transformer (Fitness). The parameters were determined as current density (s) and iron cross-section suitability factor (C). The current and new positions of crayfish were examined on a two-dimensional axis. The reason why the search space size was chosen as two-dimensional is the use of current density (s) and iron section suitability factor (C), which are two variable parameters in the objective function. These parameters are the basic elements that determine the positions of crayfish. COA initially randomly assigns positions of crayfish in the population based on values specified in the value ranges of variable parameters. The value ranges of the variable parameters are shown in Eqs. (36-37). According to the assigned position values, the fitness value of each crayfish is calculated depending on the objective function. The fitness value of each individual found represents the fitness values of the crayfish and is equivalent to the weight of the transformer [17-18], [21]. The steps of the crayfish algorithm used for transformer optimization are shown in Figure 2.

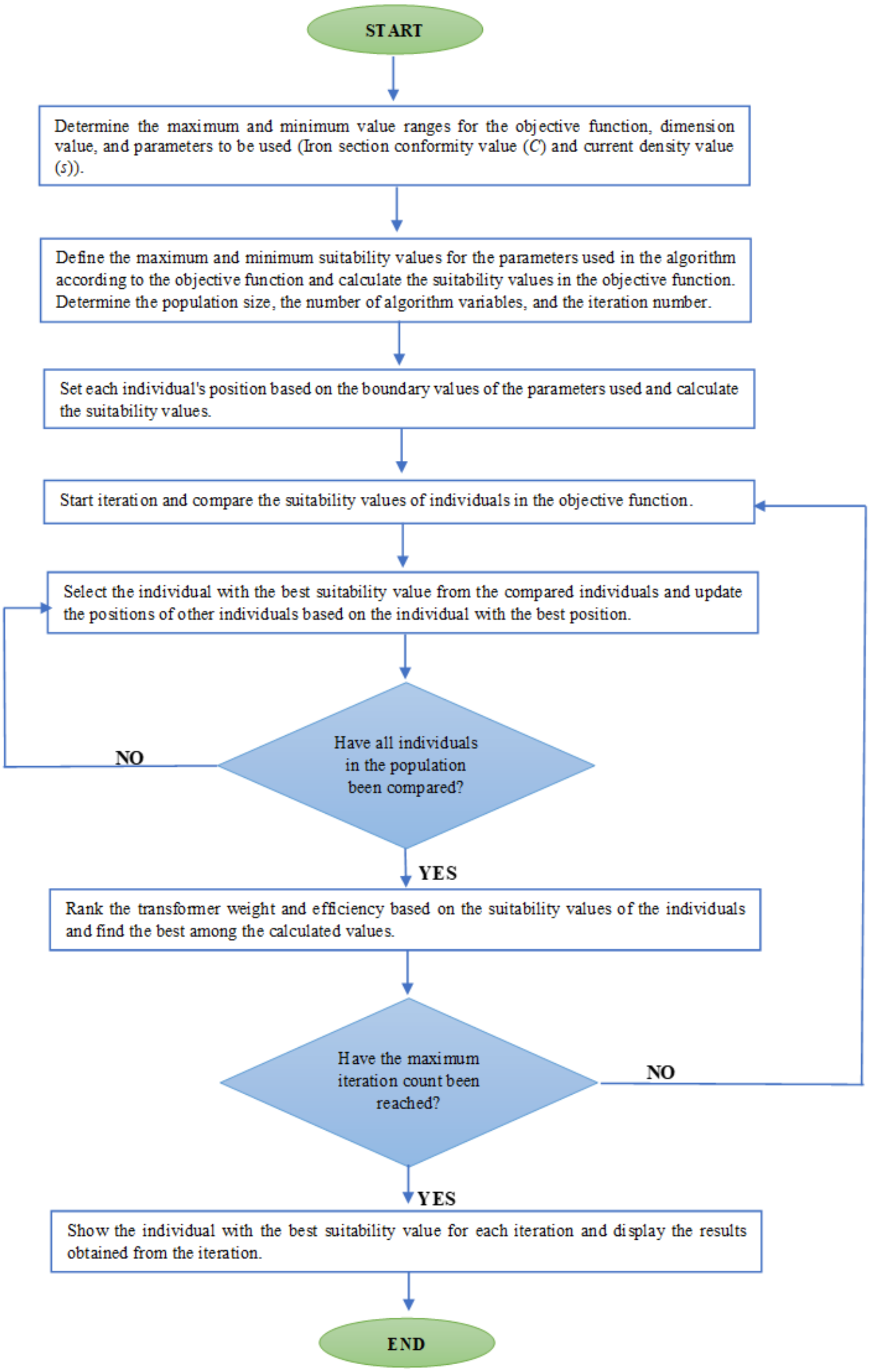

Figure 2. *Flow chart of transformer optimization with COA*

Fitness : ***minimum*** $\boldsymbol{G_T}$

$$2.2 \le s \le 3.5 \ \mathrm{A}/cm^2 \quad for \quad S = 50kVA \ and \ S = 100\mathrm{kVA} \tag{36}$$

$$4 \le C \le 6 \ cm^2\, joule^{-1/2} \quad for \quad S = 50\mathrm{kVA} \ and \ S = 100\mathrm{kVA} \tag{37}$$

Experimental Results and Discussion

All the applications in this section are coded and run on a machine with the features shown in Table 2.

Table 2. *PC specifications*

Name	Detailed settings
Hardware	
CPU	Intel i5-7300 HQ
Frequency	2.50 GHz
RAM	16 GB
Software	
Operating system	Windows 10 (64-bit)
Language	MATLAB R2022B

The Parameter Analysis Result of COA for Weight Optimization of Oil-Type Transformers

In this subsection, 50kVA and 100kVA transformers were optimized in different numbers of the maximum iterations and different population sizes and the results are shown in Tables 3-4. Looking at Table 3, there are the values obtained by the 50kVA and 100kVA transformer in maximum iteration size=100 and in population size={10, 20, 30, …, 100}. The best weight values are the same for between 10 and 100 population sizes. For the 50kVA transformer, mean weight values were obtained from the population size=50, and the best standard deviation value was obtained from the population size=60. The efficiency value of COA is it reached %96.87 from population size=40. For the 100kVA transformer, mean weight values were obtained from the population size=20, and the best standard deviation value was obtained from the population size=60. COA is it reached %97.37 of the population size=30. In Table 4, the results at the number of maximum iteration={10, 100, 1000, and 10000} obtained respectively for 50kVA and for 100kVA transformers were obtained best, worst, mean, standard deviation, and efficiency values by keeping the population same. The best and mean values for the 50kVA transformer were obtained from the number of the maximum iteration=100. The standard deviation value reached 0 at the number of the maximum iteration=1000. The best efficiency value was obtained from the number of the maximum iteration=10, and the best standard deviation value was obtained from the number of the maximum iteration=1000. The best and mean values for the 100kVA transformer were obtained from the number of the maximum iteration=10. The standard deviation value reached 0 from the number of the maximum iteration=1000. The best efficiency value was obtained from the number of the maximum iteration=10, and the best standard deviation value was obtained from the number of the maximum iteration=1000. It was observed that as the number of iterations increased, the time spent in calculating the results also increased.

Table 3. *The population size analyses results of COA for weight optimization of oil type transformers (50kVA and 100kVA, T=100)*

	G_T (Fitness)									
	50kVA									
	N=10	**N=20**	**N=30**	**N=40**	**N=50**	**N=60**	**N=70**	**N=80**	**N=90**	**N=100**
Best	**318.7821**	**318.7821**	**318.7821**	**318.7821**	**318.7821**	**318.7821**	**318.7821**	**318.7821**	**318.7821**	**318.7821**
Worst	318.7989	318.7989	318.7989	318.7864	318.7821	318.7826	318.7821	318.7821	318.7821	318.7821
Mean	318.7890	318.7871	318.7840	318.7823	**318.7821**	**318.7821**	**318.7821**	**318.7821**	**318.7821**	**318.7821**
Std	0.00833	0.0079	0.0052	0.00007	0.00005	**0.00001**	0.000060	0.00008	0.000014	0.000024
Time	**0.0647**	0.1020	0.1692	0.2164	0.2768	0.3088	0.3670	0.4088	0.4505	0.5227
	100kVA									
Best	**413.622**	**413.622**	**413.622**	**413.622**	**413.622**	**413.622**	**413.622**	**413.622**	**413.622**	**413.622**
Worst	413.623	413.622	413.622	413.622	413.622	413.622	413.622	413.622	413.622	413.622
Mean	413.622.3	**413.622.2**	**413.622.2**	**413.622.2**	**413.622.2**	**413.622.2**	**413.622.2**	**413.622.2**	**413.622.2**	**413.622.2**
Std	0.002752	0.000062	**0.000006**	0.000144	0.000403	0.000083	0.000049	0.000249	0.000034	0.000009
Time	**0.1234**	0.1532	0.1689	0.2265	0.2932	0.3709	0.4159	0.4481	0.5258	0.6169
	Efficiency									
	50kVA									
Best	0.9686	0.9686	0.9686	**0.9687**	**0.9687**	**0.9687**	**0.9687**	**0.9687**	**0.9687**	**0.9687**
Worst	0.9681	0.9681	0.9681	0.9686	0.9686	0.9686	0.9686	0.9686	0.9686	0.9686
Mean	0.9684	0.9685	**0.9686**	**0.9686**	**0.9686**	**0.9686**	**0.9686**	**0.9686**	**0.9686**	**0.9686**
Std	0.000271	0.000254	0.000166	0.000352	0.0001801	0.003841	**0.0000311**	0.006431	0.001496	0.0008106
Time	**0.0647**	0.1020	0.1692	0.2164	0.2768	0.3088	0.3670	0.4088	0.4505	0.5227
	100kVA									
Best	**0.9737**	**0.9737**	**0.9737**	**0.9737**	**0.9737**	**0.9737**	**0.9737**	**0.9737**	**0.9737**	**0.9737**
Worst	0.9681	0.9681	0.9681	0.9686	0.9686	0.9686	0.9686	0.9686	0.9686	0.9686
Mean	0.9684	0.9685	**0.9686**	**0.9686**	**0.9686**	**0.9686**	**0.9686**	**0.9686**	**0.9686**	**0.9686**
Std	0.000022	0.000616	0.00007	0.000451	0.00019	0.00002	0.000133	0.00596	0.000014	**0.000008**
Time	**0.1234**	0.1532	0.1689	0.2265	0.2932	0.3709	0.4159	0.4481	0.5258	0.6169

Table 4. *The number of maximum iteration analyses results of COA for weight optimization of oil type transformers (50kVA and 100kVA, N=100)*

	G_T (Fitness)							
	50kVA				100kVA			
	T=10	**T=100**	**T=1000**	**T=10000**	**T=10**	**T=100**	**T=1000**	**T=10000**
Best	318.7822	**318.7821**	**318.7821**	**318.7821**	**413.622**	**413.622**	**413.622**	**413.622**
Worst	318.8356	318.7821	318.7821	318.7821	414.072	**413.622**	**413.622**	**413.622**
Mean	318.7980	**318.7821**	**318.7821**	**318.7821**	413.652	**413.622**	**413.622**	**413.622**
Std	0.01497	0.000024	**0**	**0**	0.0009676	0.0000010	**0**	**0**
Time	**0. 05040**	0.5227	4.7317	48.8014	**0.06130**	0.5754	5.2751	54.4139
	Efficiency							
Best	**0.9687**	**0.9687**	**0.9687**	**0.9687**	**0.9737**	**0.9737**	**0.9737**	**0.9737**
Worst	0.9687	0.9686	00.9687	0.9687	0.9736	0.9737	0.9737	0.9737
Mean	**0.9687**	**0.9687**	**0.9687**	**0.9687**	0.9736.9	**0.9737**	**0.9737**	**0.9737**
Std	0.00000541	0.0008106	**0**	**0**	0.00968	0.000002	**0**	**0**
Time	**0.05040**	0.5227	4.7317	48.8014	**0.06130**	0.5754	5.2751	54.4139

The results of COA for weight optimization for oil-type transformers (50kVA and 100kVA)

In this subsection, the weight of 50 kVA and 100 kVA transformers was optimized using the Crayfish Optimization Algorithm (COA). In this study, current section density (*s*) and iron section suitability factor (*C*) were determined as optimization parameters, and the boundary limits are shown in Table 5. The number of maximum iterations (*T*) was determined as 1000 and the number of population size (*N*) was determined as 100.

Table 5. *The parameter settings for COA*

Parameters	**Values**
Population size (*N*)	100
Maximum iterations (*T*)	1000
Dimension (*dim*)	2
Current section density (s) Eq. (36)	[2.2 3.5] A/cm^2 for 50 kVA and 100 kVA.
Iron section suitability factor (*C*) Eq.(37)	[4 6] $cm^2\ joule^{-1/2}$ for 50 kVA and 100 kVA
Run	20

In this subsection, current density (s) and iron section suitability value (C) were obtained by keeping them within the value ranges specified in Eq. (36) and Eq. (37), and the total weight of the transformer ($\boldsymbol{G_T}$) and efficiency of the transformer (Efficiency) were obtained by using these value ranges. The results of COA for weight optimization of oil-type transformers (50 kVA and 100 kWA) are shown in Table 6. Positions of crayfish in the first population and last population (N=10 and T=1000) and weight values of the oil-type transformer (50 kVA and 100 kWA) are shown in Table 7 and Table 8. In Table 6, for the 50kVA transformer, the current density value (s) was found to be 3.01 and the iron section suitability value (*C*) was found to be 5.57. In line with the results obtained, the best result for the total weight of the 50kVA transformer ($\boldsymbol{G_T}$) was found to be 381.7821 (kg). The efficiency of the transformer (Efficiency) was obtained as 0.9686. In Table 6, for the 100kVA transformer, the current density value (s) was found to be 3.43 and the iron section suitability value (C) was found to be 5.08. In line with the results obtained, the best result for the total weight of the 100kVA transformer ($\boldsymbol{G_T}$) was found to be 413.6222 (kg). The efficiency of the transformer (Efficiency) was obtained as 0.9737.

Table 6. *The results of COA for weight optimization of oil-type transformers (50 kVA and 100 kVA)*

	50 kVA		100 kVA	
	G_T (Fitness)	Efficiency	G_T (Fitness)	Efficiency
Best	318.7821	0.9686	413.6222	0.9737
Worst	318.7821	0.9686	413.6222	0.9737
Mean	318.7821	0.9686	413.6222	0.9737
Std	0.00000005	0.000000001	00000000003	0
Time	5.275	5.275	5.921	5.921
s value	3.01		3.43	
C value	5.57		5.08	

When Table 7 is examined, the average weight of the 50kVA transformer in the first created population was found to be 322.1257 (*kg*). In the final population, the average weight of a 50kVA transformer was found to be 318.7989 (*kg*). Considering these two results, the weight decrease was calculated as 1.04%. The crayfish with the best weight loss rate is the one at the 6^{th} crayfish number. Also when Table 8 is examined, the average weight of the 100kVA transformer in the first created population was found to be 418.0716 (*kg*). In the final population, the average weight of a 100kVA transformer was found to be 413.6222 (*kg*). Considering these two results, the weight decrease was calculated as 1.07%. The crayfish with the best weight loss rate is the one with 3^{rd} crayfish number. In Figure 3, the total weight of the 50kVA and 100kVA traditional transformers and the total weight of the 50kVA and 100kVA transformers optimized with COA are shown in the column chart. The weight of the traditional oil-type 50kVA transformer is calculated as 332.28. As a result of optimization with COA, the weight of the minimized 50kVA transformer was found to be 318.7821. As a result of optimization, a weight reduction of %4.23 was observed. The weight of the traditional oil-type 100kVA transformer is calculated as 436.3 and as a result of optimization with COA, the weight of the minimized 100kVA transformer was found to be 413.622. As a result of optimization, a weight reduction of %5.48 was observed. In Figure 4, the efficiency of the 50kVA and 100kVA traditional transformer and the efficiency of the 50kVA and 100kVA transformer optimized with COA are shown in the column chart. The efficiency of the traditional oil-type 50kVA transformer is calculated as %95. As a result of optimization with COA, the efficiency of the maximized 50kVA transformer was found to be %96.87 and the efficiency of the traditional oil type 100kVA transformer is calculated as %92 and as a result of optimization with COA, the efficiency of the maximized 100kVA transformer was found to be %97.37.

Table 7. *Positions of crayfishes in the first crayfish in population and last crayfish in population (N=10 and T=1000) and weight values of the oil type transformer (50 kVA)*

Crayfish number	First population	Transformer weight value (kg)	Last population	Transformer weight value (kg)	Percentage decrease of transformer weight amount (%kg)
1.	[3.2591 4.3152]	319.8311	[3.1187 4]	318.7989	0.32
2.	[3.3775 5.9412]	320.3109	[3.1187 4]	318.7989	0.47
3.	[2.3651 5.9143]	324.8965	[3.1187 4]	318.7989	1.91
4.	[3.3874 4.9708]	320.5807	[3.1187 4]	318.7989	0.56
5.	[3.0221 5.6006]	318.9718	[3.1187 4]	318.7989	0.05
6.	**[2.3268 4.2838]**	**326.8014**	**[3.1187 4]**	**318.7989**	**2.51**
7.	[2.5620 4.8435]	323.7798	[3.1187 4]	318.7989	1.56
8.	[2.9109 5.8315]	321.5064	[3.1187 4]	318.7989	0.85
9.	[3.4448 5.5844]	322.1570	[3.1187 4]	318.7989	1.05
10.	[3.4544 5.9190]	322.4217	[3.1187 4]	318.7989	1.13
Mean		**322.1257**		**318.7989**	**1.04**

Table 8. *Positions of crayfishes in the first crayfish in population and last crayfish in population (N=10 and T=1000) and weight values of the oil type transformer (100 kVA)*

Crayfish number	First population	Transformer weight value (kg)	Last population	Transformer weight value (kg)	Percentage decrease of transformer weight amount (%kg)
1.	[3.5000 5.2694]	415.3344	[3.4316 4.3655]	413.6222	0.41
2.	[3.5000 4.8121]	415.3344	[3.4316 4.3661]	413.6222	0.41
3.	**[2.4985 5.9306]**	**430.5718**	**[3.4316 4.4527]**	**413.6222**	**4.1**
4.	[3.3215 4.4156]	415.2456	[3.4316 4.3520]	413.6222	0.39
5.	[3.3215 4.9224]	415.2456	[3.4316 4.3661]	413.6222	0.39
6.	[2.9992 5.0877]	416.7304	[3.4316 4.2795]	413.6222	0.75
7.	[3.0772 5.3746]	418.3367	[3.4316 4.3673]	413.6222	1.13
8.	[3.3215 5.0407]	415.2456	[3.4316 4.3661]	413.6222	0.39
9.	[2.6728 5.0008]	424.0008	[3.4316 4.3219]	413.6222	2.50
10.	[3.4737 5.0477]	414.6716	[3.4316 4.3661]	413.6222	0.25
Mean		**418.0716**		**413.6222**	**1.07**

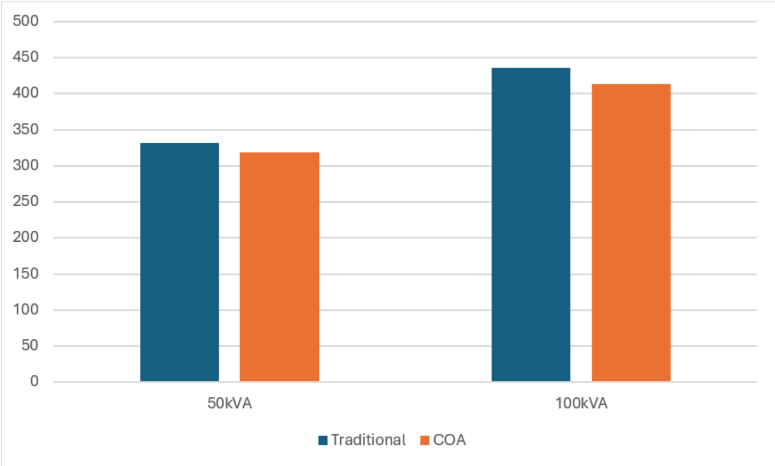

Figure 3. *Minimized total weight values of transformers at different power levels with traditional and COA*

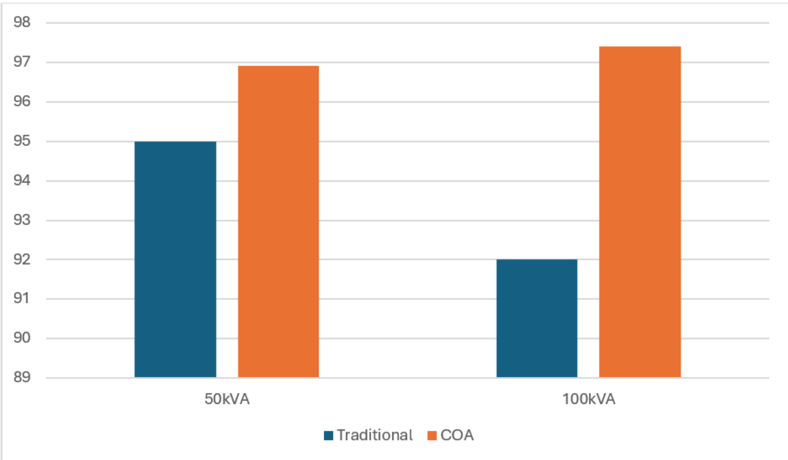

Figure 4. *Maximized efficiency values of transformers at different power levels with traditional and COA*

The Comparison Results of COA and other Algorithms (GWO, FA, ZOA, and OOA) for Weight Optimization of Oil-Type Transformers (50 Kva And 100 Kva)

In this subsection, 50 kVA and 100 kVA transformers are compared with other heuristic algorithms (Firefly Algorithm (FA) [18], Gray Wolf Optimization (GWO) [21], Osprey Optimization Algorithm (OOA) [31], and Zebra Optimization Algorithm (ZOA) [32]) in the literature. While GWO and FA results are available in the literature, ZOA and OOA results were obtained for the first time in this paper for comparison. Although ZOA and OOA are newly proposed algorithms in recent years, GWO and FA are older heuristics. The results of COA were compared with both new heuristic algorithms and old heuristic algorithms in this study. In Table 9, the current density value (s) and iron section suitability factor (C) are presented as the results of optimized with traditional, optimized with GWO**,** optimized with COA, optimized with FA, optimized with ZOA, and optimized with OOA for 50kVA and 100kVA transformers (for different N and T values). The obtained total weights (G_T) and efficiency percentages were compared. For N=100 and T= 10000, the traditional 50kVA transformer has a weight of 332.28

(kg) and an efficiency percentage of 95%. The weight of the GWO-optimized 50kVA transformer is 229.47(kg) and its efficiency is 95.1%. The weight of the transformer for 50kVA optimized with COA was 318.78 (kg) and its efficiency was found to be 96.87%. For N=10 and T=10, The weight of the oil-type transformer for 50kVA optimized with FA was found to be 224.3866(kg) and its efficiency was 97%. The weight of the transformer for 50kVA optimized with COA was 319.6341 (kg) and its efficiency was found to be 96.87%. GWO achieved a weight reduction of 31% and 21% at 50kVA and 100kVA, respectively. FA achieved a reduction of 11% for 50kVA. In the results obtained, COA achieved a reduction of 2.51% and 4.1% for 50kVA and 100kVA, respectively. As a result of these comparisons, it was seen that COA could not achieve the desired weight reduction in other compared results and power levels. There are various reasons for this situation. First of all, COA's ability to discover and exploit variable values in the search space as much as FA and GWO is not balanced. At this point, COA needs to be improved. Another issue is that when the transformer efficiency found by FA and GWO is compared with the transformer efficiency found by COA, there is no significant difference. This means that although COA could not minimize the total iron weight sufficiently, this situation did not affect the efficiency. In addition, the accuracy of the total iron calculation equations of FA and GWO should be re-examined.

In Table 9, in addition to COA, transformer weight has been optimized by using ZOA ~~(~~Zebra optimization algorithm~~)~~ [32] and OOA (Osprey optimization algorithm~~)~~ [31], which are in the literature and have not been used in transformer weight optimization before, the parameters used in transformer weight optimization its weight was optimized using the parameters used in transformer weight optimization, current density value (s) and iron cross-section suitability factor (C) and The population size (N) = 100 and the number of maximum iteration (T) = 1000 were kept constantly.

When the obtained results are examined, it is observed that although COA, ZOA, and OAA obtain very close results, COA's results are generally better than other heuristics (ZOA and OOA). ZOA and COA found the total weight for 50kVA as 318.7821, while OOA found the total weight of the transformer as 318.7823. COA efficiency was found 96.87 for 50kVA, and ZOA and OOA found the same values at 96.86. For 100kVA, COA found the total weight of the transformer as 413.6220, ZOA found the total weight of the transformer as 413.6223 and OOA found the total weight of the transformer as 413.6240. All three heuristic optimization algorithms calculated the same efficiency as 97.37 for 100kVA. This is due to the fact that COA searches the search space better than the ZOA and OOA heuristic algorithms and is successful in capturing better local points on the solution sets it finds. COA also appears to be a heuristic that is more robust against local solution traps. However, it also shows that it needs to be improved to find a higher efficiency and minimum total iron weight than heuristics such as ZOA and OOA.

Table 9. *The Comparison of* Traditional*, COA, GWO, FA, ZOA, and OOA results for 50 kVA and 100 kVA on weight values of the oil type transformer (N=100 and T=10000)*

Algorithms		***S=50kVA***	***S=100kVA***	***Parameter settings***
Traditional	**G_T (kg)**	332.28	436.3	***N*=100 and *T*=10000**
	Efficiency(%)	95	92	
	C value	4.6	5-6	
	S value	2.2	2.6	
COA	**G_T(kg)**	318.7821	413.622	
	Efficiency(%)	96.87	97.37	
	C value	5.7616	5.36	
	S value	3.015	3.43	
GWO [21]	**G_T(kg)**	229.47	338.3	
	Efficiency(%)	95.1	92.1	
	C value	3.02	4.7	
	S value	2.4	2.7	
COA	**G_T(kg)**	319.6341	-	***N*=10 and *T*=10**
	Efficiency (%)	96.87	-	
	C value	5.7052	-	
	S value	3.1502	-	
FA [18]	**G_T (kg)**	224.3866	-	
	Efficiency(%)	97	-	
	C value	4.4553	-	
	S value	3.500	-	
COA	**G_T (kg)**	318.7821	413.6220	***N*=100 and *T*=1000**
	Efficiency (%)	96.87	97.37	
	C value	5.7616	5.36	
	S value	3.015	3.43	
ZOA [32]	**G_T (kg)**	318.7821	413.6223	
	Efficiency (%)	96.86	97.37	
	C value	5.0977	5.2725	
	S value	3.0147	3.4315	
OOA [31]	**G_T (kg)**	318.7823	413.6240	
	Efficiency (%)	96.86	97.37	
	C value	4.231	4	
	S value	3.0147	3.4316	

Discussion on the Results

In this study, the newly proposed COA algorithm was examined and its success was tested in optimizing 50 kVA and 100 kVA transformer weights. COA was proposed by Jia et al. [7] in 2023. COA is a metaheuristic algorithm built by simulating the feeding and lifestyles of crayfish during the exploration and exploitation phases in a continuous search space. When the literature is examined, different problems have been solved with COA and its success has been tested. However, COA has been tested for the first time in this study in the optimization of transformer weights. In this study, it is aimed to minimize the total weight of transformers and maximize their efficiency by using COA. There are two types of variables that affect the calculation of the total transformer weight. These are transformer current density (*s*) and iron section compatibility (*C*) restrictions. The aim is to determine the variables (*s* and *C*) corresponding to the lowest total transformer weight with COA. First of all, a detailed population size and maximum iteration analysis with COA were performed in this study. The parameters affecting the performance of COA are of great importance for the study. The success of COA increases linearly as the population size and the maximum iteration number increase. After selecting the most appropriate parameter settings with COA, total iron weight and efficiency (%) were calculated. The performance of the COA population at each step was analyzed and presented to the readers. COA results are much more minimal than G_T results at 50kVA and 100kVA calculated by traditional methods and the efficiency (%) obtained with COA is much more maximum. This shows that heuristic algorithms are effective in calculating the transformer's total iron weight (G_T). When the success of COA was compared with the GWO and FA algorithms at 50 kVA, it was seen that COA could not minimize the G_T value sufficiently. However, it was also seen that this situation did not seriously affect the efficiency (%) value. COA and GWO found the efficiency (%) value as 96.87 at 50 kVA. FA found the efficiency (%) value as 97 at 50 kVA. At 100 kVA, FA results were not compared with COA results since they were not in the literature. GWO and COA were compared under similar conditions at 100 kVA. When G_T results were examined, a similar situation was observed at 100 kVA as at 50 kVA. While GWO minimized the G_T value better than COA, this situation was not reflected in the efficiency (%) value. According to the efficiency (%) value, COA obtained a better value than GWO. While COA found the efficiency (%) value as 97.37, GWO found it as 92.1. It was observed that COA increased the transformer efficiency value to a better level. It is thought that the inconsistency between the COA, FA, and GWO results in the G_T calculation may be due to the differences in the G_T calculation equations used in FA and GWO. In addition, it is due to the fact that COA could not explore the search space sufficiently or was caught in local traps. This shows that COA needs to be improved. The OOA and ZOA algorithms selected from the literature and newly proposed in recent years were also compared with the COA results. When the G_T results were examined at 50 kVA and 100 kVA values, the three algorithms (COA, ZOA, and OOA) produced similar results and the efficiency (%) values corresponding to these G_T results were similar. At 50 kVA, the best G_T results were obtained by COA (318.7821) and ZOA (318.7821), while the worst G_T results were obtained by OOA (318.7823). At 50 kVA, the best efficiency (%) results were obtained by COA (96.87), while the worst efficiency (%) results were obtained by ZOA (96.86) and OOA (96.86). At 100 kVA, the best G_T result was obtained by COA (413.6220), while the worst G_T results were obtained by ZOA (413.6223) and OOA (413.6240). At 100 kVA, all three algorithms (COA, ZOA, and OOA) obtained similar efficiency (%) results (efficiency (%) = 97.37). When the *C* and *s* variable values affect the minimum G_T and maximum efficiency (%) results were examined, it was observed that the algorithms obtained similar values. When the results are examined in more detail, COA has achieved a better G_T and efficiency (%) results at 50 kVA and 100 kVA compared to the newly proposed heuristic algorithms (ZOA and OOA). This proves that COA has a good balance between exploration and exploitation capabilities in the search space compared to ZOA and OOA. This is due to COA being less caught in local traps and finding the global best solution.

Conclusions

In this study, different power levels used in the transmission and distribution of electrical energy at fixed frequency and power are examined. It is aimed to optimize the weight of transformers with the Crayfish Optimization Algorithm (COA). COA was used to optimize the weight of 50kVA and 100 kVA transformers. Fitness function determined as total weight (G_T). The problem dimensions are the current density value (s) and iron section suitability factor (C) parameters. They were used to minimize the total weight (G_T). In this study, population size analysis and the number of the maximum iteration analysis were performed for 50kVA and 100kVA. The effects of ten different population sizes (10, 20, 30, 40, 50, 60, 70, 80, 90, and 100) and four different maximum iteration numbers (10, 100, 1000, and 1000) on COA were examined in detail. Similar values were obtained starting from population size 50 for S=50kVA. The results on yield were similar when the population size was approximately 30 for S=50kVA. Similar values were obtained starting from population size=20 for S=50kVA. The results on yield were similar when the population size was approximately 30 for S=50kVA. COA started to find similar results when the maximum number of iterations was 100. The positions of the crayfish in the first and last population and the weight values of the oil-type transformer (50 kVA and 100 kVA) are shown in the study (N = 10 and T = 1000). As a result of the optimization, the total weight (G_T), for 50 kVA was calculated as 318.7821, the efficiency as (%) 96.87, the current density value (s) as 5.7616, and the iron section suitability factor (C) as 3.015, for 100kVA the total weight (G_T), was calculated as 413.6220, the efficiency as (%) 97.37, the current density value (s) as 5.36, and the iron section suitability factor (C) as 3.43. The results obtained, COA achieved a reduction of 2.51% and 4.1% for 50kVA and 100kVA, respectively. The results obtained were compared with four different heuristic algorithms selected from the literature. The total iron weight found by COA is less than the transformer iron weight calculated by the traditional method. In contrast, the transformer efficiency is better. This situation makes the calculation of the transformer's total iron weight with heuristic algorithms more advantageous. COA results were also compared with heuristic algorithms selected from the literature (GWO, FA, ZOA, and OOA). While the total iron weight results of COA, FA, and GWO were not consistent, the efficiency found with COA was similar to FA and GWO. This situation is due to the differences between the total iron weight calculations with FA and GWO and the total iron weight calculations with COA. COA results were also compared with the recently proposed ZOA and OOA algorithms. The calculation of the transformer's total iron weight with ZOA, OOA, and COA heuristic algorithms was carried out for the first time in this study. When the results were compared, COA obtained better results than ZOA and OOA in both total iron weight and efficiency at 50 kVA and 100 kVA. The motivation of the study is that oil-type transformer weight calculation with COA has never been done in the literature. In addition, the results of the ZOA and OOA heuristic algorithms used in oil-type transformer weight calculation problem comparisons constitute a source for the literature in this study. The success of COA in real-world problem solutions is demonstrated in this study. This study can be used as a source for future transformer weight optimization studies using metaheuristic algorithms. In future studies, it is planned to hybridize COA with different heuristic algorithms and increase the success level of COA.

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