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Radio-frequency circular integrated inductors sizing optimization using bio-inspired techniques

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ABSTRACT

In this article, a comparative study is accomplished between three of the most used swarm intelligence (SI) techniques; namely artificial bee colony (ABC), ant colony optimization (ACO), and particle swarm optimization (PSO) to carry out the optimal design of radio-frequency (RF) spiral inductors, the three algorithms are applied to the cost function of RF circular inductors for 180 nm beyond 2.50 GHz, the aim is to ensure optimal performance with less error in inductance, and a high-quality factor when compared to electromagnetic simulation. Simulation experiments are achieved and performances regarding convergence velocity, robustness, and computing time are checked. Also, this paper shows an impact study of technological parameters and geometric features on the inductance and the quality factor of the studied integrated inductor. The building method of constraints design with algorithms used has given good results and electromagnetic simulations are of good accuracy with an error of 2.31% and 4.15% on the quality factor and inductance respectively. The simulation shows that ACO provides more accuracy in circuit size and fewer errors than ABC and PSO, while PSO and ABC are better in terms of convergence velocity.

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1. INTRODUCTION

Integrated inductors are a crucial electrical component for filtering and tuning objectives in many circuit blocks applied to radio-frequency analysis and design [1]. Circular inductors modeling for radio-frequency integrated circuit (RFIC) is a complicated assignment. Various combined unsuspected problems are expected, and many sizing and simulation constraints must be taken into account. In the fact, there are sensitive levels that should be considered when customizing inductors, such as measuring test inductors for verification, and an optimal pick out of an electromagnetic (EM)-simulation software. The main applications of integrated inductors include voltage controlled oscillators (VCO) [2], [3], low noise amplifiers (LNA) [4], and direct current (DC) voltage controllers [5].

Furthermore, problems of optimizing for analog circuits are becoming more and more complex, mainly because of the various constraints generated by the race for miniaturization. In the last decade, meta-heuristics are applied to resolve many complex problems [6], its advantages are manifested in being "easily" modified and adapted according to the specificities and requirements of the problem [7]. A significant number of metaheuristics have been applied for problem-solving of the optimized design of analog circuits, such as artificial bee colony (ABC) [8], [9], genetic algorithms (GA) [10], [11], tabu search (TS) [12], simulated annealing (SA) [13], differential evolution (DE) [14], [15], ant colony optimization (ACO) [16], [17], Jaya algorithm (JA) [18], particle swarm optimization (PSO) [19], [20], salp swarm algorithm (SSA) [21], firefly algorithm (FA) [22], and the gravitational search algorithm (GSA) [23].

For modeling circular spiral inductors for 180 nm beyond 2.50 GHz, an application of three of the most known and most used metaheuristics in the literature; namely ABC, ACO, and PSO is proposed. Many works have been carried out for spiral inductors sizing, the fundamental proceedings to design an integrated circuit (IC) are: formulation, modeling, optimization, and implementation [24]–[26], this process can be recurrent to ameliorate the optimization results until a reasonable solution is found [27]. These algorithms belong to the swarm intelligence technique, which is an efficient technique for solving nondeterministic polynomial time (NP)-hard problems [28], the concept of this technique is to mimic the behavior of social insects which are active as a swarm. SI techniques capitalize on a sequence of possible solutions to explore the search space to find the more preferable's. In this work, the design constraints are built and respected to reduce the effect of parasitic phenomena. In addition, a study of the influence of parameters geometric, the metal underpass and the metal thickness on the quality factor, and the inductance of spiral circular inductors was conducted to form a comprehensive view of the impact of these parameters separately.

The next sections of the paper layout introduce in that way: section 2 is consecrated for the overview of the algorithms applied. Subsequently, section 3 highlights the performance optimization of integrated inductors where the simulation experiments obtained are checked against advanced design system (ADS) momentum simulation. Afterward, section 4 highlights the influence of geometric features and technological parameters on the quality factor and the inductance. Finally, the conclusion is offered in section 5.

2. SI TECHNIQUES: A BRIEF INTRODUCTION TO PSO, ACO, AND ABC

Many complex problems are no longer considered difficult due to swarm intelligent optimization algorithms, that supply rapid and reliable methods for solutions. This returns to its features such as robustness, flexibility, self-organization, parallel, and distributive. In this section, an overview of the general principles of PSO, ACO, and ABC techniques is given.

2.1. Particle swarm optimization

It is a metaheuristic method that is suitable to optimize nonlinear continuous functions. The PSO algorithm is proposed by Kennedy and Eberhart in 1995 [29], this technique is inspired by the connotation of swarm intelligence, overwhelmingly seen in the animal set, like shoals and flocks, In the PSO algorithm, a swarm of birds flying everywhere should find a point that depends on various cases to land and survival by minimizing and maximizing respectively, the danger of the presence of predators, and the availability of food. In this situation, the movement of the birds is a choreography; the birds still fly simultaneously for a time till the best area available for food and security is assured, then the flock lands at the same time. As a consequence, the determination of which location the whole swarm should land is a complicated issue [30]. The steps of the PSO algorithm are shown in Figure 1.

2.2. Ant colony optimization

In ACO, the artificial ants seek out optimal solutions to a given optimization problem. The ACO algorithm is the first swarm intelligence-based algorithm, it was proposed by Dorigo *et al.* in the 1990s [31], inspired by the foraging actions of ants in the wild, and the phenomena known as stigmergy, a term used by Grasse in 1959 [32]. Essentially, ACO mimics the foraging behavior of social ants in a colony and utilizes pheromone to simulate local interactions and communications between ants. The pheromone is precipitated by each ant and gradually evaporates over time. The system of the evaporation model might differ, be based on the variant and form of ACO used in applications, in this case, the incremental deposition and exponential decay of pheromone are both vastly applied. The steps of the ACO algorithm are presented in Figure 2 [33].

2.3. Artificial bee colony

In 2005 a new swarm intelligent technique was proposed by Karaboga *et al.* [34] namely: the ABC algorithm, which was inspired by the intelligent foraging behavior of the honey bees swarm. The ABC is a population-based algorithm and the placement of a food source represents a potential solutions for the optimization problem, as a rule, there are three kinds of bees in bee colonies: employed bees, scout bees, and onlooker bees where the nectar amount of a food source is in agreement with the fitness of the related solution. Usually, the ABC algorithm steps could be outlined as shown in Figure 3.

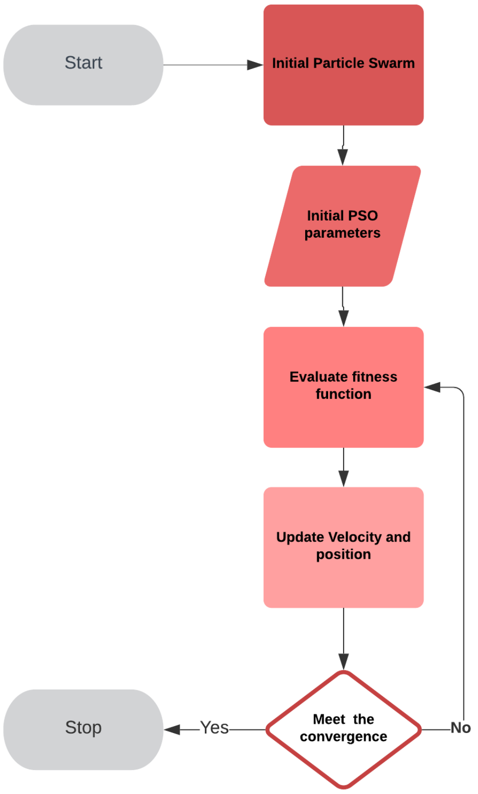


Figure 1. PSO algorithm flowchart

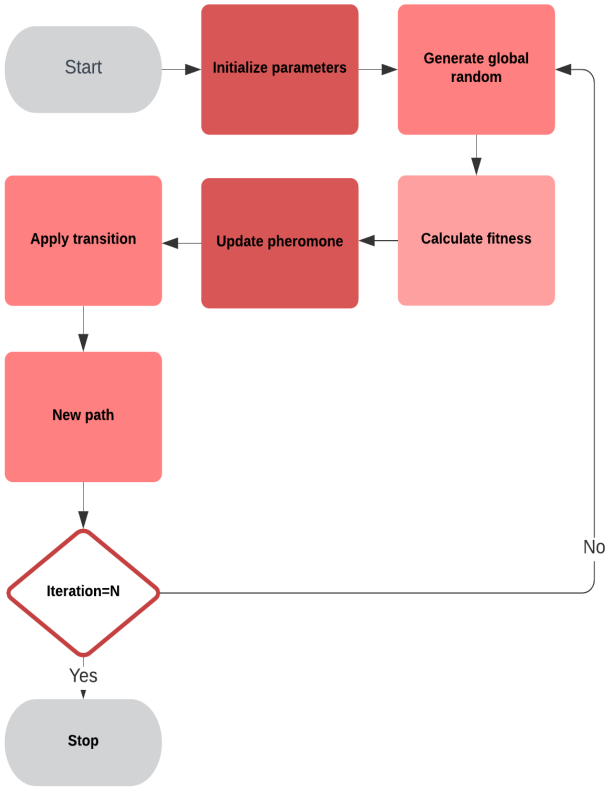


Figure 2. ACO algorithm flowchart

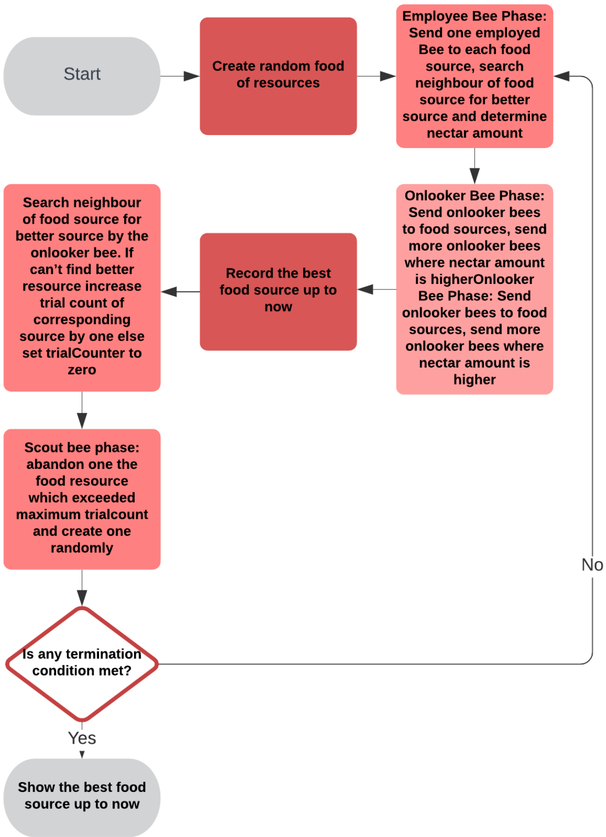


Figure 3. ABC algorithm flowchart

3. PERFORMANCE OPTIMIZATION OF RF INTEGRATED INDUCTORS

To compare the performance of the three techniques PSO, ABC, and ACO, the function presented in (3) is optimized, the essential target is to maximize the quality factor presented in (2) for an inductance equal to 6 nH. Afterward, the simulation experiments are checked using a non-commercial EM simulator. The respective codes of the three techniques were implemented using MATLAB software. Iterations number (IN) is equal to 500, and the population number (PN) is equal to 100. Table 1 gives algorithms parameters values. Generally, the problem for RF inductors can be formulated as [27]:

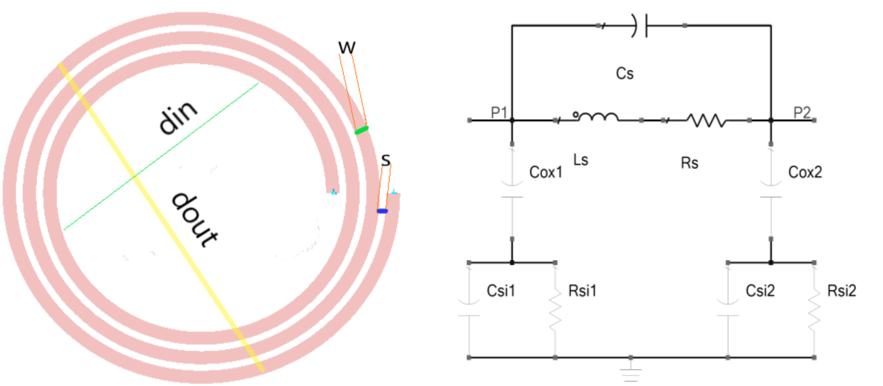
Determine: D= (D_{out}, s, w, n)
To maximize: Q
Subject to: L_s=6 nH, SRF_{min}= 12 GHz…

Table 1. Algorithms parameters

Algorithm	Parameter	Value
ACO	Heuristics factor (β)	1.00
	Quantity of deposit pheromone (Q)	0.10
	Evaporation rate (ρ)	0.70
	Pheromone Factor (α)	1.00
PSO	Inertia Weight Damping Ratio	0.99
	Global Learning Coefficient	2.00
	Inertia Weight	1.00
	Personal Learning Coefficient	1.50
ABC	Number of food sources	NP/2
	Employed bees Number	50% of the swarm
	Onlooker bees Number	50% of the swarm

3.1. RF spiral inductors

To model a spiral circular inductor, it is necessary to determine suitable values for the main parameters which are: the number of turns (n), the line spacing (s), the line width (w), the inner length of a side (d_{in}) and the outer length of a side (d_{out}). Figures 4(a) and 4(b) show the layout of the circular integrated inductor and the physical π model of the studied inductor respectively. The values of these elements in terms of technological parameters and geometric features are acquired with the set of equations offered in [27]. Other important parameters can be expressed such as, the inductor length, the inductor area, and the average diameter (d_{avg}) [27].



(a) (b)

Figure 4. Circular integrated inductor (a) layout model and (b) physical π-model [35]

Expressions used to measure the inductance (L_s) and the quality factor (Q) are presented in (1) and (2) [36]. The quality factor (Q) is equal to zero at a specific value of frequency expressed as the self- resonant frequency (SRF). The coefficients c_1, c_2, c_3, and c_4 are not dependent on the technology, they are depending on the structure of the inductor. The inductance is measured in nH for dimensions in µm, while ρ is the fill ratio. The process uses a high resistivity silicon substrate on which two metallic copper levels are formed, the losses by the joule effect in the conductors are modeled by the resistance R_s which generally vary with the frequency to correctly translate the skin and proximity effects. Figure 5 shows the silicon substrate of the spiral inductor [37].

$$Ls = 0.5 \,.\, \mu_0 . n^2 . d_{avg} . c_1 \left(\ln\left(\frac{c_2}{\rho}\right) + c_3 . \rho + c_4 . \rho^2 \right) \tag{1}$$

$$Q = \omega . \frac{Ls}{Rs} . \frac{2Rp}{2Rp + \left(\left(\omega . \frac{Ls}{Rs}\right)^2 + 1\right)} \times \left(Rs . \left(1 - (Cs + 0{,}5 . Cp) . \left(\frac{Rs^2}{Ls} + \omega^2 . Ls \right) \right) \right) \tag{2}$$

Figure 5. Shot view of the spiral inductor: silicon substrate [38]

3.2. Results and discussions

This section highlights the inductor sizing-optimization method. Besides, the optimization results obtained by MATLAB software are presented, whereas analytical results are investigated by ADS momentum simulation software. The cost function was formulated as presented in (3):

$$Cost_F = \left(\frac{1}{Q} + 10^9 (L - Lsreq) \right) + S * C(x) \tag{3}$$

where:

$$C(x) = \sum_i^n Ci(x) \tag{4}$$

or

$$Ci(x) = 1 \;\; \text{if} \;\; gi(x) > 0 \quad \text{Or} \quad Ci(x) = 0 \;\; \text{if} \;\; gi(x) \leq 0$$

where *C*(x) is the sum of constraints, S is the penalty coefficient, and *g*(x) is the constraint function. The physical and technological parameters are appearing in Table 2. The layout parameters were determined in accordance with constraints shown in Table 3. Simulation experiments of a two-port circular inductor for an operating frequency of 2.50 GHz are shown in Table 4 with parameters in µm and inductance nH. The SRF is constrained with $SRF_{min} \geq 12$ GHz. To check the optimization process, Figure 6 presents the convergence of ACO, PSO, and ABC algorithms for L_s equal to 6 nH.

Subsequently, for more accuracy regarding optimization precision of ACO, PSO, and ABC, each algorithm is turned on fifty times, then the best, the std, average values, and computing times for the quality factor function are listed in Table 5. The maximum iteration number is $iter_{max} = 500$. Figure 7 represents the distribution of optimum solutions with ACO, PSO, and ABC using the boxplot representation. Computer configurations utilized are symbolized as follows: processor (CPU) Core i5-7200U CPU @ 2.50 GHz 2.71 GHz and memory (RAM) 4 GB.

It is apparent from simulations that, the convergence velocity of the ACO and the PSO, are all in a good range, but the ABC is the best. It is conspicuous from the boxplot distribution curve, that PSO and ABC are faster than ACO, while ACO presents a strong optimization precision when is turned on fifty times but is needed big-time for searching. Boxplot distribution shows that PSO and ABC present strong robustness than ACO respectively, while ACO and ABC accord the maximum quality factor when turned on fifty times.

Table 2. Values of physical and technological parameters

Symbol	Quantity	Value
ρ	Substrate resistivity	0.20 Ω.m
t	Metal thickness	2.80 μm
t_{sub}	Substrate thickness	600 μm
σ	Metal conductivity	4×10^{7} Ω/m
ε_r	The relative permittivity of the silicon	11.9
$t_{ox\_m1\text{-}m2}$	Oxide thickness between spiral and underpass	0.66 μm
ε_0	Permittivity of vacuum	8.85×10^{-12} F/m
μ	The magnetic permeability of free space	$4\pi \times 10^{-7}$ H/m
ε_r	The relative permittivity of the Oxide	4.00
ε_0	Permittivity of vacuum	8.85×10^{-12} F/m
t_{ox}	The thickness of the oxide	6.42 μm
C_1	Coefficient c_1	1.00
C_2	Coefficient c_2	2.46
C_3	Coefficient c_3	0
C_4	Coefficient c_4	0.20

Table 3. Layout parameters boundary

Design variable	Lower bound	Upper bound
n	1.50	10
d_{out}	140 μm	300 μm
s	2.00 μm	2.50 μm
w	3.00 μm	20 μm

Table 4. Optimization results

	L_{req}	L_{An}	Q	n	s	w	d_{out}
ABC	6.00	6.27	15.37	6.26	2.08	12.77	265.30
PSO	6.00	6.25	15.07	7.10	2.24	10.10	221.24
ACO	6.00	6.50	14.49	7.00	2.60	9.26	219.48

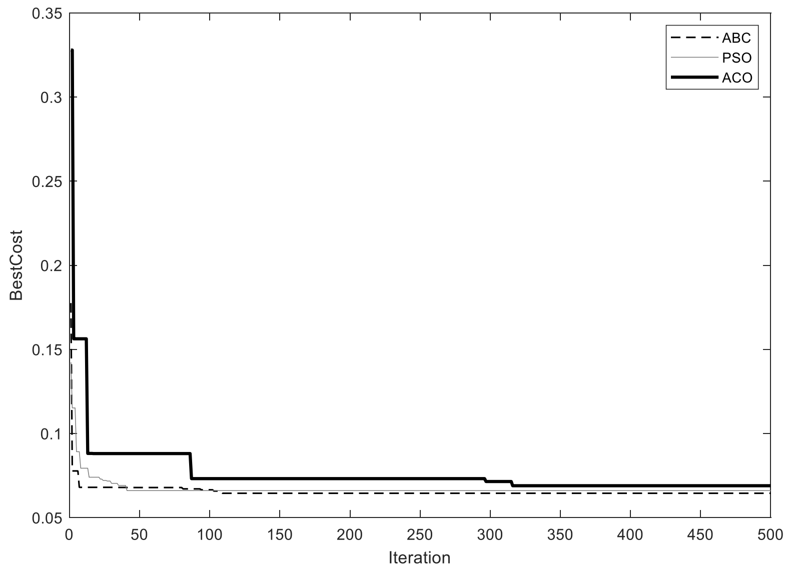


Figure 6. The objective function against the number of iterations

To confirm experiment results, momentum simulation was conducted for L_s=6 nH, the electromagnetic simulations of the inductance and the quality factor are shown in Figure 8 and Figure 9 respectively. Comparisons between analytical results and momentum simulations are summarized in Table 6.

It is apparent from the electromagnetic simulation that the error is 15.52% for inductance for PSO, 4.15% for ACO, and 5.58% for ABC. While the error of the Q-factor at a frequency equal to 2.50 GHz is 17.71% for PSO, 2.31% for ACO, and 15.81% for ABC.

The ACO algorithm offers fewer errors compared to ABC and PSO. The optimization precision of ACO, PSO, and ABC, are all in a good range, but ACO is the best. However, ACO did not give the highest value of quality factor during simulation experiments but it was the most accurate when comparing results using momentum simulation.

Table 5. The robustness analysis results and the average computing times

	ABC	PSO	ACO
Average	0.0631	0.0679	0.0633
Std	0.0357	0.0122	0.1300
Times (s)	260.64	184.92	421.82

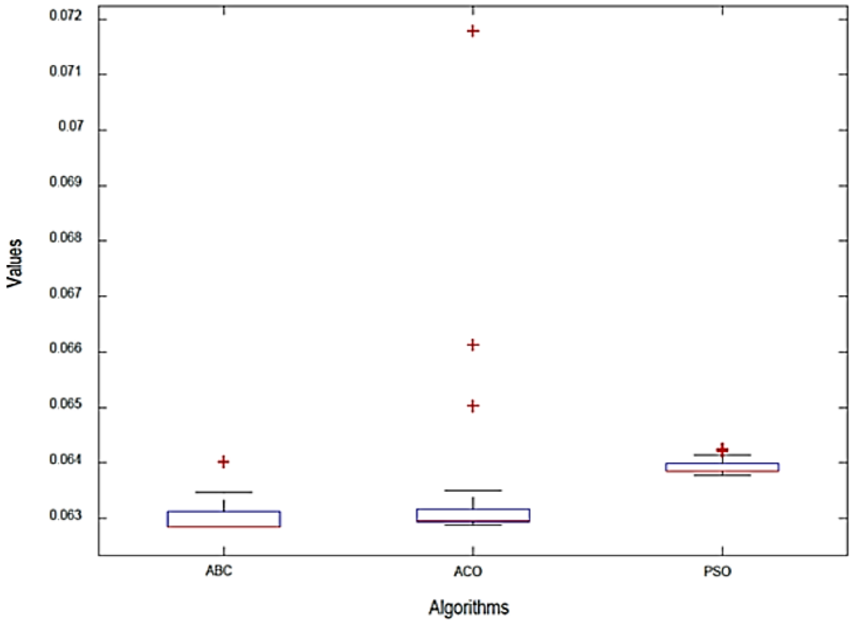


Figure 7. Distribution of optimum solutions using the boxplots representation

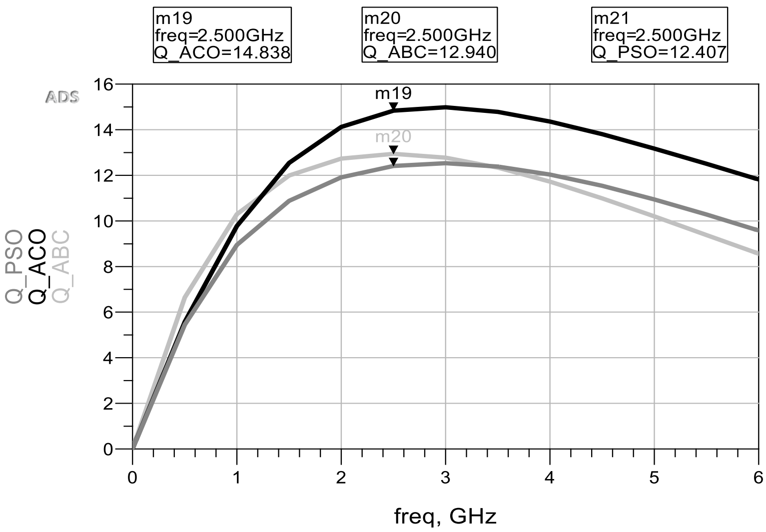


Figure 8. Momentum simulation of the quality factor

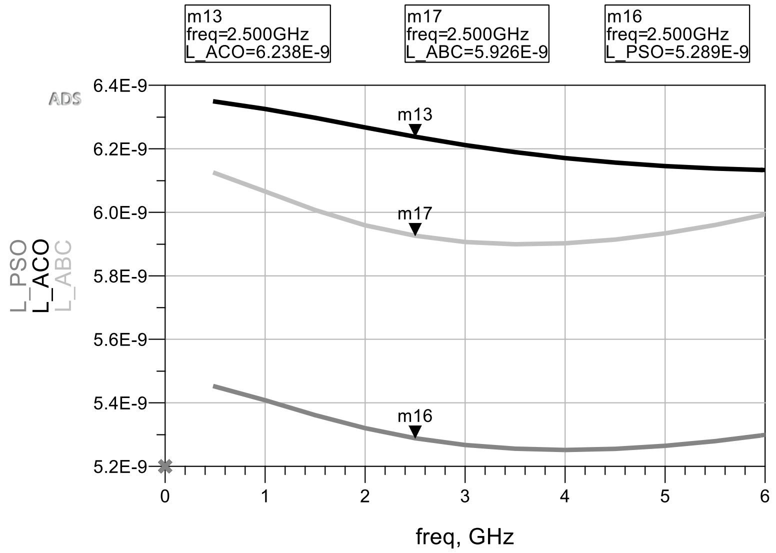


Figure 9. Momentum simulation of the inductance

Table 6. Optimization results and their comparison with ADS momentum simulations

	L_{req} (nH)	L_{an} (nH)	L_{ads} (nH)	Error (%)/ L_{req}	Error (%)/ L_{an}	Q_{an}	Q_{ads}	Error (%)
ABC	6 .00	6.27	5.92	1.33	5.58	15.37	12.94	15.81
PSO		6.25	5.28	12.00	15.52	15.07	12.40	17.71
ACO		6.50	6.23	3.83	4.15	14.49	14.83	2.31

4. IMPACT OF TECHNOLOGICAL AND GEOMETRICAL PARAMETERS ON THE INDUCTANCE AND THE QUALITY FACTOR

The objective of this section is to analyze the influence of technological parameters and geometrics of circular spiral inductors for radiofrequency circuit design. Firstly, the inductor was optimized using the ant colony technique at 2.50 GHz, to determine the optimal geometrical dimensions s, n, d_{out}, and w. Then, the impact of those parameters, and the influence of metal thickness and metal underpass have been studied on the inductance and the quality factor of the integrated inductor.

By converting the metal thickness from 0.1 to 10 µm, the quality factor can be increased. Figure 10 shows the impact of the metal thickness and the metal underpass on the Q. For the metal underpass, the quality factor was increasing slightly. For the technology of 0.18 µm, the optimal value of the metal underpass must be higher than 0.60 µm.

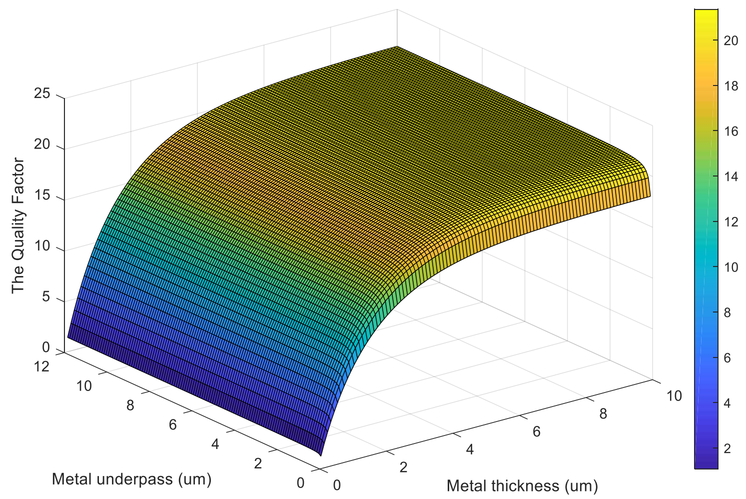


Figure 10. Influence of metal thickness and metal underpass on the quality factor

To seek out the impact of parameters geometric on the characteristics of the inductance, we carried out parameters influence analysis between *s*, *w*, d_{out}, and *n*, which are positioned next to each other. The analysis methods build on the study of inductor optimized by ACO for L_s=6 nH that has been measured in section 2. The results are presented in Figures 11 to 14.

On the other hand, it may be concluded from the gradient of every map of solutions that the outer diameter has a strong impact on the inductance. When d_{out} increases the inductance increases as well. For the quality factor, the width (*w*) has the upper hand of influence, the quality factor decreases when the width (*w*) increases or decreases, it also affects the value of inductance (L_s) but less so than its effect on the Q-factor.

Nevertheless, the inductance and series resistance decrease as a function of track width (*w*). Indeed, when the width increases. The effective section of the conductor becomes larger and contributes to the reduction of this resistance, as resistance decreases faster than reactance, the quality factor improves.

L_s increases slightly for an increment of 0.1 um in the spacing (*s*). On the other hand, the spacing (*s*) has a weak influence on the quality factor, it does not affect all the Q. It is therefore in our interest to use the smallest spacing (*s*) allowed by the technological process. For the number of turns (*n*), an increase in its value increases the inductance (L_s). But for the quality factor, there is a value of n where the Q is at the highest value and then starts decreasing around this optimal point whether the number of turns increases or decreases.

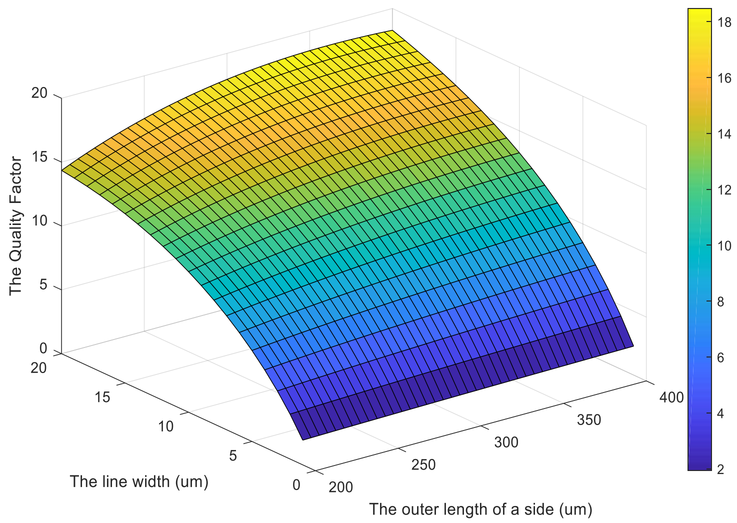


Figure 11. Impact of the line width and the outer diameter on the quality factor

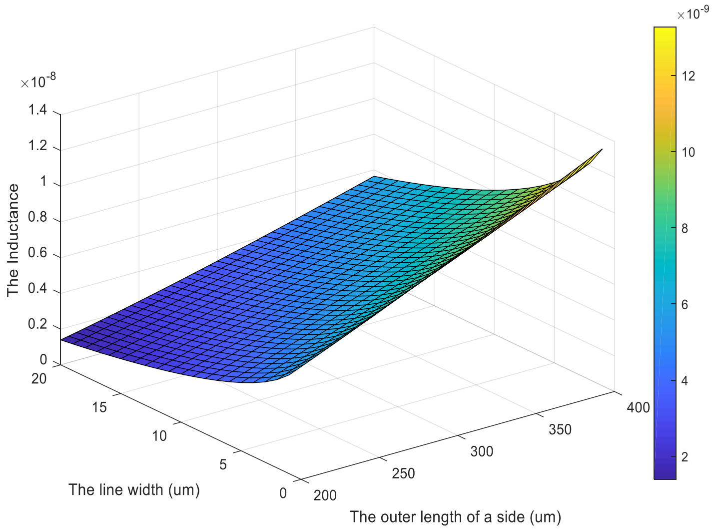


Figure 12. Impact of the line width and the outer diameter on the inductance

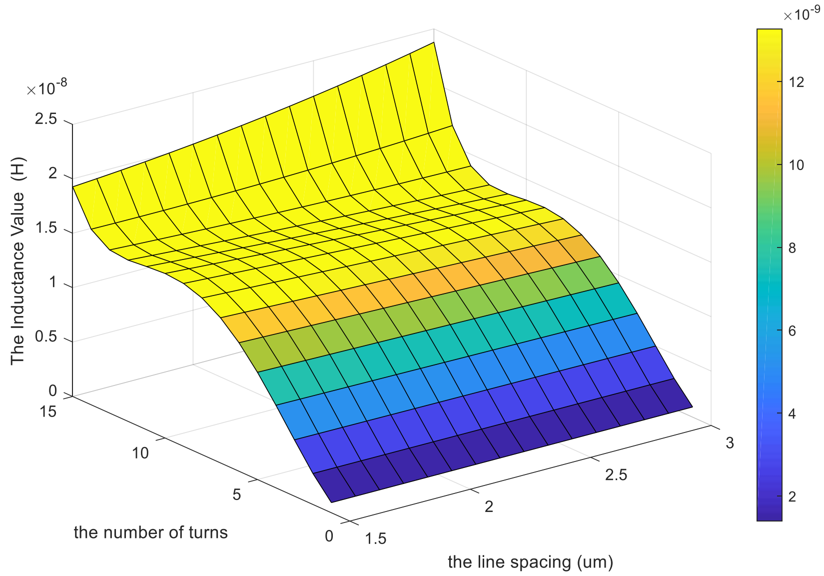


Figure 13. Impact of the number of turns and the line spacing on the inductance

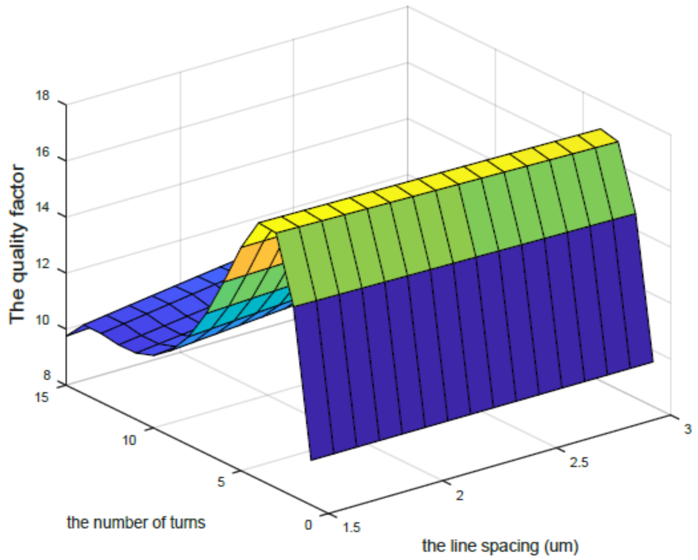


Figure 14. Impact of the number of turns and the line spacing on the quality factor

5. CONCLUSION

The current study suggests a comparative study among three metaheuristic optimization algorithms of swarm intelligence vastly applied in electronic problems. The artificial bee colony (ABC), the ant colony optimization (ACO), and the particle swarm optimization (PSO) were used for optimal sizing of the circular integrated inductor. The building of design constraints gave perfect results, and this is evident with simulations. Although the algorithm could appear to have a great performance during simulation experiments, its effectiveness appears through a practical simulation, especially when dealing with the RF integrated inductor design problem which is a complex process related to multiple design constraints. In this regard, the ACO algorithm has shown good efficiency than ABC and PSO when comparing analytical results against electromagnetic simulation. Simulation experiments and the momentum simulation, all have been approaching high accuracy, the ACO algorithm has been offered good results in terms of the inductor area and a good accuracy compared to ABC and PSO, however, the ABC presents strong robustness, and has the best convergence velocity, whereas the PSO is faster.

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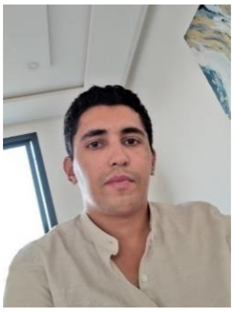

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