International Journal of Engineering Trends and Technology
ISSN: 2231 – 5381 / https://doi.org/10.14445/22315381/IJETT-V71I3P232

Volume 71 Issue 3, 312-324, March 2023

Original Article

Improvement of Nature-Based Optimization Methods for Solving Job shop Scheduling Problems

Hakim Jebari[1], Siham Rekiek[2], Kamal Reklaoui[3]

[1,3] Research Laboratory in Engineering, Innovation and Management of Industrial Systems (2ISMI), Faculty of Science and Technique of Tangier, University Abdelmalek Essaâdi, Morocco
[2]Intelligent Automation Laboratory, The International Higher Institute of Tourism of Tangier (ISITT), Morocco

[1]Corresponding Author : hjebari1@yahoo.fr

Received: 19 January 2023 Revised: 18 March 2023 Accepted: 22 March 2023 Published: 25 March 2023

Abstract *- Scheduling is a key decision-making process within the industrial manufacturing sectors. Effective scheduling is crucial for enhancing the company's key performance indicators and competitiveness. Job shop scheduling is used extensively in real-world businesses and is challenging to solve due to its NP-hard complexity. Nature-inspired optimization methods have proven to solve various difficult optimization issues successfully. This paper presents nature-based multi-hybrid methods for solving job shop scheduling issues. The extensive experiments of these proposed methods are carried out to assess their performance in all well-known reference instances. An in-depth analysis of other methods available in the literature is also conducted to validate and compare the reliability and efficacy of the proposed methods. The computational results demonstrate that the proposed methods have achieved high performance and have provided better results. The proposed methods were more competitive and effective for the considered problem.*

Keywords *- Hybridization, Job shop, Nature-inspired method, Optimization, Scheduling.*

1. Introduction

Scheduling is one of the most crucial matters for production systems. It is the decision-making process on how to assign resources across various job opportunities. Scheduling implies allocating resources over a certain period to complete a range of jobs. In production scheduling, resources are machinery, while activities are a variety of job operations. Performance metrics are either Cmax, delay, deadlines, etc.

Job shop scheduling can be implemented in production processes and effectively affects the production time and factory production cost [1]. Consequently, solving Job shop scheduling problems makes the manufacturer more competitive. The job shop scheduling issue is one of the largest and most complex issues of the NP class [2]. Hence, it is challenging to solve.

In industry, the job shop scheduling issue is quite common and is used in many instances. Job shop scheduling issue is defined as creating an operational schedule for N jobs on M machines. Jobs are not related to each other. Each job is constituted by many operations which have to be performed in sequence. The aim is to reduce the Cmax., which is the total time for all the jobs completed. Thus, it is an issue of optimization.

This paper introduces nature-inspired multi-hybrid optimization approaches to solve job shop scheduling problems.

The rest of the paper comprises the following major sections: Section II provides the literature review. Section III describes the material and method. Section IV presents the analysis and discussion of the results. Section V provides the conclusion with future research. The last section lists the references.

2. Literature Review

On the one hand, the literature draws on the authors' accumulated background in previous works and published in various articles. On the other hand, a general review of the literature on work connected with the job shop scheduling issue. The papers studied show that most of the work focuses on testing the developed techniques on the benchmark or the problems generated. The job shop scheduling benchmark instances are FT [3], LA [4], ABZ [5], ORB [6], YN [7], SWV [8], TA [9], and DMU [10].

Researchers have developed numerous methods, such as exact methods, heuristics, metaheuristics, and hybrid methods [11], to ensure optimum or almost optimum solutions to job-shop scheduling problems. Table 1 shows some methods developed to solve job shop scheduling issues.

Table 1. The Developed Methods for Solving Job Shop Scheduling Problems

Proposed Method	Reference
Parallel BA	[12]
EA (island models) + TS	[13]
EA+TS	[14]
EA+SS / EA+TS	[15]
EA+TS+Akers method	[16]
INSA+NIS+TS	[17]
TSAB	[18]
Parallel EA (MPI's collective communication) + SA	[19]
RL+CNN	[20]
SA	[21]
TS+SBP	[22]
FDS+LNS	[23]
EA+TS	[24]
TS / TS-logistic regression model	[25]
CRO-WTC / GA-WTC / SEJSP	[26]
EA+LS	[27]
Parallel ABC / ABC	[28]

These developed methods have been tested on the benchmark instances FT [12], ABZ [13-15], YN [14-17], ORB [13,26,27], TA [13] [15-25], DMU [15,16,20,21,24,25], LA [12,14,26], SWV [14,16,23,24,28]. A few studies conducted in the job shop scheduling field are presented in [29].

However, to the fullest knowledge of the authors, very few contributions are available within the literature that examines the multi-hybridization of nature-inspired optimization approaches to solve job shop scheduling issues and conduct an extensive comparative study.

3. The Material and Method

Optimization is the procedure of improving something, testing variants of an original design and using the information obtained to enhance the idea. The optimization issues can be observed in many fields, including computer systems, economy, manufacturing systems, etc. Over the past few years, some methods of optimization have been developed using an analogy inspired by nature [29-32].

The methods inspired by nature offer distinct benefits, like simplicity, flexibility, and the capacity to solve difficult issues. All nature-based methods comprise the ability to explore and exploit. The disadvantage is that these methods have unbalanced exploration and exploitation procedures. Consequently, the ability of nature-based methods to solve various optimization issues effectively and efficiently needs to be enhanced. Increasing the problem-solving capability of nature-inspired methods is usually obtained through the alteration of existing algorithms, hybridization of algorithms and development of new approaches.

The authors of this paper focus on the popular methods of optimization inspired by nature, that is, the Artificial Bee Colony method (ABC) and the Bat method (BA).

3.1. Artificial Bee Colony Method (ABC)

The Artificial Bee Colony algorithm (ABC) belongs to the methodological optimization class called the nature-based optimization algorithm. It draws inspiration from the intelligent foraging behaviors of the honeybee swarm. This method was first established by Karaboga in 2005 [33] to address multi-dimensional and multi-modal optimization issues [34]. It delivers best-in-class solutions in a wide range of areas [35-38] and improves results by performing a variety of iterations with obtainable alternatives to solve complex issues. A comprehensive outline of ABC usage is accessible in [50].

In the method of Artificial Bee Colony, three types of foraging bees are available: employed bees, onlooker bees, and scout bees. The procedure of the method of Artificial Bee Colony is outlined in [29].

The method of Artificial Bee Colony has the following advantages:

- Facility for operation and implementation.
- Global and local search capacity.
- Ability to solve a range of optimization problems.
- Capability to integrate with other algorithms and enhance the performance of fixed optimization issues.

The disadvantages of the method of Artificial Bee Colony are the following:

- Parameter settings, time and precision, are needed for adjustment.
- The probabilistic of local search of the algorithm.
- Random initialization.

3.2. Bat Method (BA)

The Bat Algorithm (BA) [40,41] is an innovative population-based technique appropriate for challenging optimization issues. It is a nature-based technique developed by Yang [41] that utilizes frequency adjustment to imitate the basic behavior of bat echolocation.

The concept of echolocating bats is a type of sonar that helps them find their prey and distinguish the various insects in total darkness. The echolocation makes it easier for bats to measure a flying insect's size, position, range, velocity and direction. The bats fly with variable frequencies, sound intensity and pulse emitting rates, which can be used to develop bat algorithm upgrade equations. A solution vector for an issue is a position vector for a bat in the search area.

For the implementation of the suggested algorithm, an idealized set of rules are given in the following manner [40]:

1. The echolocation used by All bats to detect the distance and perceive the difference between food and barriers alike, even in the dark.
2. Bats fly arbitrarily randomly with speed v_i^t in position x_i^t with a fixed frequency f_i, the wavelength β variable, and the intensity A_i^t looking for prey. They automatically regulate the transmitted pulse frequency and the r_i^t pulse emission rate, depending on their target's proximity.
3. The sound intensity varies from a large A_i^t looking for prey to a constant minimal value in the direction of the prey.

The BA algorithm is very strong because it uses the frequency adjustment method for increasing the range of solutions in the population (intensification). Simultaneously, the BA system uses the instinctive zoom procedure to preserve stability during the process of exploring.

The major disadvantage of the standard BA algorithm is the sudden transition to the exploitation phase by rapidly varying A_i^t and r_i^t. This rapid change can cause stagnation in the early phases [42].

Numerous researchers have acknowledged this limitation of the BA algorithm and have supplied strategies for improving the performance of this algorithm by using novel quasi-random sequence torus [43], fuzzy logic [42], chaotic sequence [44], deferential operator and Levy flight concepts [45]. The BA algorithm is highly powerful in that it combines the main advantages of other algorithms.

3.3. The Proposed Methods

New methods will become more necessary when nature-inspired methods do not function properly. Combining two nature-inspired methods may be very helpful in achieving a more efficient method. The hybrid methods inspired by nature will be attractive as they combine the advantages of multiple methods, increase their efficiency by balancing exploitation and exploration processes and overcome the disadvantages of existing methods.

The proposed hybridization between the artificial Bee Colony method (ABC) and the Bat method (BA) has been developed in this paper according to the LTH hybrid class [46]. These methods, called HABCBA and AHABCBA, consist of coupling the artificial Bee Colony method (ABC) with the Bat method (BA). The uniform randomized generating (URG) [51] is employed in the proposed methods HABCBA and AHABCBA to enhance the population of possible solutions. In the proposed methods HABCBA, the Bat method (BA) is added in the employed bees phase and (or) in the onlooker bees phase, and (or) in the scout bees phase of the Artificial Bee Colony method (ABC). Conversely, in the proposed methods AHABCBA, the employed bee phase, the onlooker bee phase, and the scout bee phase are replaced through the Bat method (BA). The HABCBA and AHABCBA methods are described in Table 2. These proposed methods, HABCBA and AHABCBA, focus mainly on the minimization of Cmax. The procedures for implementing the HABCBA2 and AHABCBA1 methods are described in Figure 1.

Table 2. The Description of the HABCBA and AHABCBA Methods

	AHABCBA / HABCBA			
	Initialization phase	**Employed bee phase**	**Onlooker bee phase**	**Scout bee phase**
AHABCBA1	URG	Replace by (BA)		
HABCBA1	URG	Add (BA)		
AHABCBA2	URG	Replace by (BA)	Replace by (BA)	
HABCBA2	URG	Add (BA)	Add (BA)	
AHABCBA3	URG	Replace by (BA)	Replace by (BA)	Replace by (BA)
HABCBA3	URG	Add (BA)	Add (BA)	Add (BA)
AHABCBA4	URG		Replace by (BA)	
HABCBA4	URG		Add (BA)	
AHABCBA5	URG		Replace by (BA)	Replace by (BA)
HABCBA5	URG		Add (BA)	Add (BA)
AHABCBA6	URG			Replace by (BA)
HABCBA6	URG			Add (BA)
AHABCBA7	URG	Replace by (BA)		Replace by (BA)
HABCBA7	URG	Add (BA)		Add (BA)

HABCBA2

Initialize :
Input parameters.
Number required for the termination criterion.
Solutions number.
Employed bees' number.
Onlooker bees' number.
Number of scout bees.
Possible solution populations by equation (1).
Compute the fitness value for each solution function (7).
Determine the most appropriate solution.
g=1
While (g< The specified generations number)
g=g+1
For (each employed bee)
Generate a new solution by Applying BA.
Determine the fitness value of these solutions using function (7).
Determine the best solution.
End For
For (each onlooker bee)
Generate a new solution by Applying BA.
Choose the ith solution associated with the probability value (p_i) using
function (9).
Determine the fitness value of these solutions using function (7).
Determine the best solution.
End For
Generate a new solution based on the transmission function (10).
Compute the fitness value for these solutions using function (7).
Determine the best scout bee amongst the solutions produced.
Compare (scout bee's best solution, employed bee's best solution,
onlooker bee's best).
Stock the best solution in the scout bee's phase and the remain
solutions in the next iteration.
Find the best solution from the scout bee's phase.
End While

AHABCB

Initialize :
Input parameters.
Number required for the termination criterion.
Solutions number.
Employed bees' number.
Onlooker bees' number.
Number of scout bees.
Possible solution populations by equation (1).
Compute the fitness value for each solution function (7).
Determine the most appropriate solution.
g=1
While (g< The specified generations number)
g=g+1
For (each employed bee)
Applying BA.
Identify the current best solution.
End For
For (each onlooker bee)
Generate a new solution based on the function (8).
Choose the ith solution associated with the probability value (p_i) using
function (9).
Determine the fitness value of these solutions using function (7).
Determine the best solution.
End For
Generate a new solution based on the transmission function (10).
Compute the fitness value for these solutions using function (7).
Determine the best scout bee amongst the solutions produced.
Compare (scout bee's best solution, employed bee's best solution,
onlooker bee's best).
Stock the best solution in the scout bee's phase and the remain
solutions in the next iteration.
Find the best solution from the scout bee's phase.
End While

Fig. 1 The procedures of HABCBA2 and AHABCBA1

Initialize :
Bat population x_i^t ,∀ i = {1, 2, . . ., n}.
Velocity v of the n bats.
Pulse emission rate r_i^t.
Loudness A_i^t .
Specify the pulse frequency vel; at position x_i^t.
For all x_i^t
Compute objective function of all n bats $F_i = f\ (x_i^t)$.
End For
Classify the bat population according to their fitness values.
Identify the current best bat solution x_i^{best}
c = 1
While (c< Maximum number of iterations)
c = c + 1
Update A_i^t as (5).
Update r_i^t ras (6).
For (loop over all n bats and all D-dimensions)
Adjust frequency as (2).
Update velocities as (3).
Update new solutions as (4).
If (rand > r_i^t)
Make new solution using Lévy Flight as
$x_i^t = x_i^{best} + \delta \Theta\ L\lambda\ (S)$
End If
Verify if the new solution is in the problem area.
If (True)
Move to next step.
Else
Apply problem-bound constraints.
End
Evaluate the objective function at new solution created as
$F_k = f\ (x_i^t)$
If ((rand <A_i^t) or ($F_k < F_i$))
Accept the new solution.
End If
Classify the bat population.
Find the current best solution x_i^{best}
End For
End While

Fig. 2 The procedure of the BA method

The procedure of the Bat method (BA) is illustrated in Figure 2.

4. Results and Discussion

The proposed methods HABCBA and AHABCBA are developed in the Java programming language on a machine that has the following configuration: Processor: Intel core i7, CPU speed: 2.5 GHz, RAM: 8 GB, OS: Windows 10. For each proposed method, HABCBAX and AHABCBAX, certain configuration settings are used for its effective functioning. The experiments were conducted using the same configuration parameters.

The possible solution population is generated as follows [51]:

$$PS = LB + Rand\ [0,\ 1](UB - LB) \quad (1)$$

The position, velocity and frequency updates in the echolocation behavior are made using the following equations [40]:

$$vel_i = vel_{min} + (vel_{max} - vel_{min})\ \beta \quad (2)$$

$$v_i^t = v_i^{t-1} + \left(x_i^{t-1} - x_i^{best}\right) vel_i \quad (3)$$

$$x_i^t = x_i^{t-1} + v_i^t \quad (4)$$

v_i^t *and* x_i^t are the velocity and position values.
x_i^{best} is the global best location.
β is the random distribution frequency vector within the range [0,1].
vel_i is the velocity increment.

The loudness A_i^t and the rate of pulse emission r_i^t are according to the following equations [40]:

$$A_i^t = \alpha A_i^{t-1} \quad (5)$$

$$r_i^t = r_i^{t-1}(1 - e^{-\gamma(t-1)}) \quad (6)$$

α *and* γ are constants.

The fitness value for each solution in the ABC phase is as below [48]:

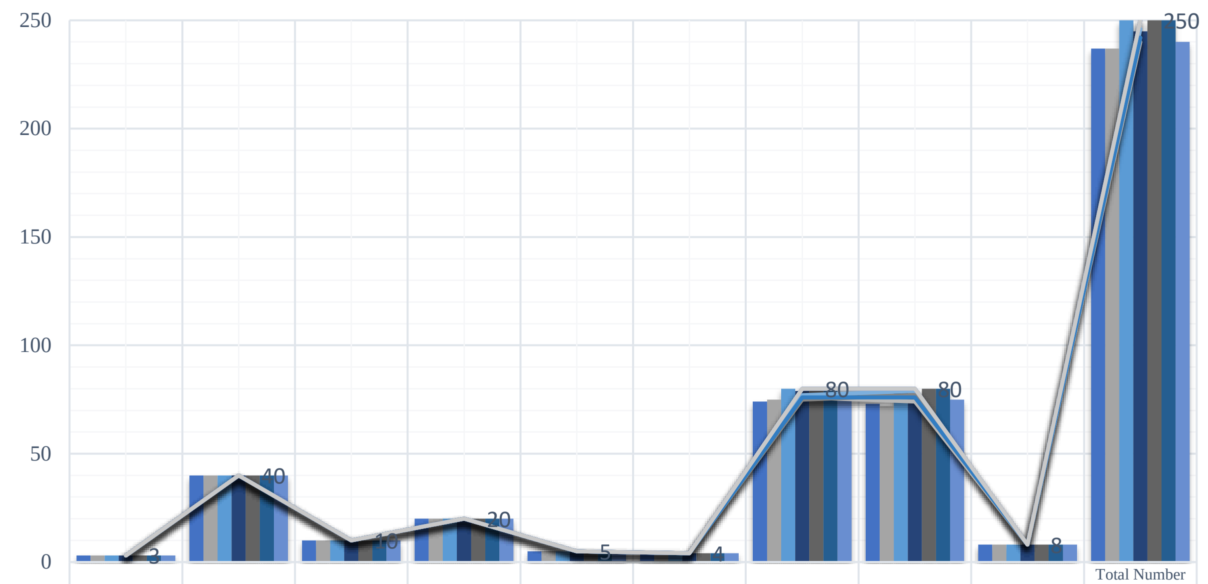
$$fit_i = \frac{1}{(1+f_i)}\ \ if\ f_i \geq 0\,;\ \ fit_i = 1 + \left|(f_i)\right|\ if\ f_i < 0 \quad (7)$$

Where f_i is the objective function value of i^{th} solutions.

The memory function is updated during the employed bees phase as follows [48]:

$$y_{ij} = x_{ij} + Rand\ [-1, 1]\left(x_{ij} + x_{kj}\right), k \neq i \quad (8)$$

y_{ij} is a new achievable dimension value of the solutions that is changed by the value of its precedent solutions x_{ij}.



	FT (3)	LA (40)	ORB (10)	SWV (20)	ABZ (5)	YN (4)	TA (80)	DMU (80)	CAR (8)	Total Number of Benchmark Instances
AHABCBA1	3	40	10	20	5	4	74	73	8	237
HABCBA1	3	40	10	20	5	4	75	72	8	237
AHABCBA2	3	40	10	20	5	4	80	80	8	250
HABCBA2	3	40	10	20	5	4	79	76	8	245
AHABCBA3	3	40	10	20	5	4	80	80	8	250
HABCBA3	3	40	10	20	5	4	80	80	8	250
AHABCBA4	3	40	10	20	5	4	75	75	8	240
HABCBA4	3	40	10	20	5	4	76	74	8	240
AHABCBA5	3	40	10	20	5	4	77	79	8	246
HABCBA5	3	40	10	20	5	4	80	80	8	250
AHABCBA6	3	40	10	20	5	4	75	77	8	242
HABCBA6	3	40	10	20	5	4	76	76	8	242
AHABCBA7	3	40	10	20	5	4	80	80	8	250
HABCBA7	3	40	10	20	5	4	80	80	8	250

Fig. 3 The experimental findings of the proposed methods AHABCBA and HABCBA

The probability value linked to the source of food p_i in the onlooker bee phase is the following [48]:

$$p_i = \frac{fit_i}{\sum_{k=1}^{SN} fit_k} \tag{9}$$

fit_i is the fitness value of i^{th} the solution.
SN is the number of possible solutions.

The function of transmission during the scout phase is set as follows [49]:

$$x_i^j = x_{min}^j + rand\,[0,1]\left(x_{max}^j - x_{min}^j\right) \tag{10}$$

x_{min}^j is the lower limit of the search zone.
x_{max}^j is the upper limit of the search zone.

In order to evaluate the performance of the proposed methods HABCBA and AHABCBA, these have been tested in all well-known reference instances existing in the literature. The results obtained by these methods are analyzed and compared against the best-known result (BKS) found by other methods. The experimental findings are presented in Figure 3.

From Figure 3, it can be seen that:

1. The proposed methods, HABCBA and AHABCBA, are provided with the best results compared to those achieved by other methods.
2. The solutions of the proposed methods HABCBA3 (hybridized in its three phases), HABCBA5 (hybridized in its scout bee and onlooker bee phase), and HABCBA7 (hybridized in its scout bee and employed bee phase) are 100% equal to the most well-known solutions in all reference instances.
3. The solutions of the proposed methods AHABCBA2 (in its three phases), AHABCBA3 (hybridized in its employed bee and onlooker bee phase), and AHABCBA7 (hybridized in its scout bee and employed bee phase) are 100% equal to the most well-known solutions in all reference instances.

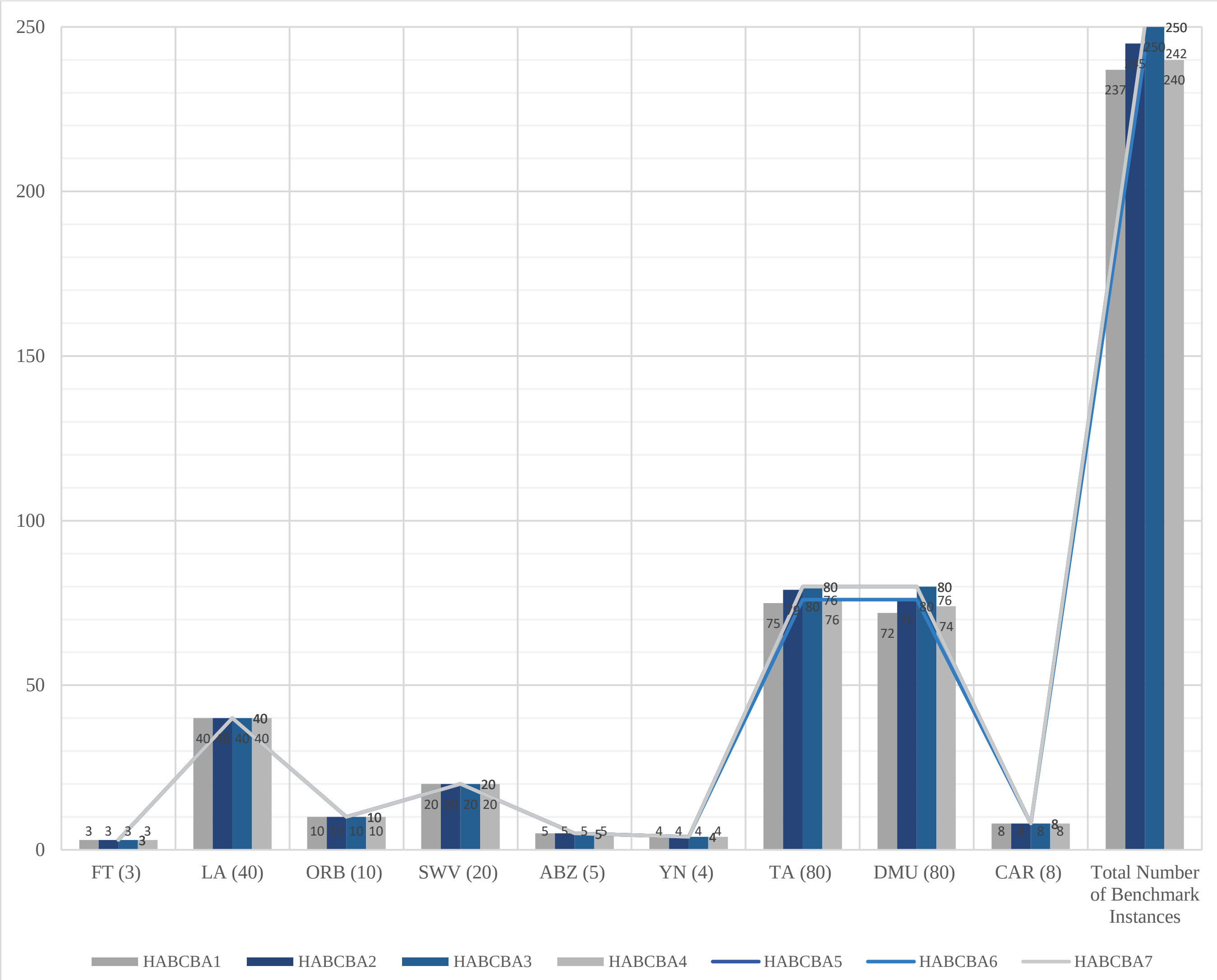


Fig. 4 The performances comparative of the suggested methods HABCBA

4. The solutions of all the proposed methods, HABCBA and AHABCBA, are 100% equal to the most well-known solutions in FT (3), LA (40), ORB (10), SWV (20), ABZ (5), YN (4), and CAR (8).
5. Only the solutions of the proposed methods HABCBA3, HABCBA5, HABCBA7, HABCBA2, AHABCBA3, and AHABCBA7 are 100% equal to the most well-known solutions in TA (80) and DMU (80).

The performances comparative of HABCBA, based on the hybridization number, is given in Figure 4.

From Figure 4, it can be seen that:

1. The results of HABCBA hybridized in its three phases are equal to the result of HABCBA hybridized in its scout bee and onlooker bee phase.
2. The results of HABCBA hybridized in its three phases are equal to the result of HABCBA hybridized in its scout bee and employed bee phase.
3. The results of HABCBA hybridized in its scout bee and onlooker bee phase is equal to the result of HABCBA hybridized in its scout bee and employed bee phase.
4. The HABCBA hybridized in its two phases provided better results than the HABCBA hybridized in its one phase.
5. The HABCBA hybridized in its scout bee and onlooker bee phase provided better results than the HABCBA hybridized in its onlooker bee and employed bee phase.
6. The HABCBA hybridized in its scout bee and employed bee phase provided better results than the HABCBA hybridized in its onlooker bee and employed bee phase.
7. The HABCBA hybridized in its scout bee phase provided better results than the HABCBA hybridized in its onlooker bee phase or employed bee phase.
8. The HABCBA hybridized in its onlooker bee phase provided better results than the HABCBA hybridized in its employed bee phase.

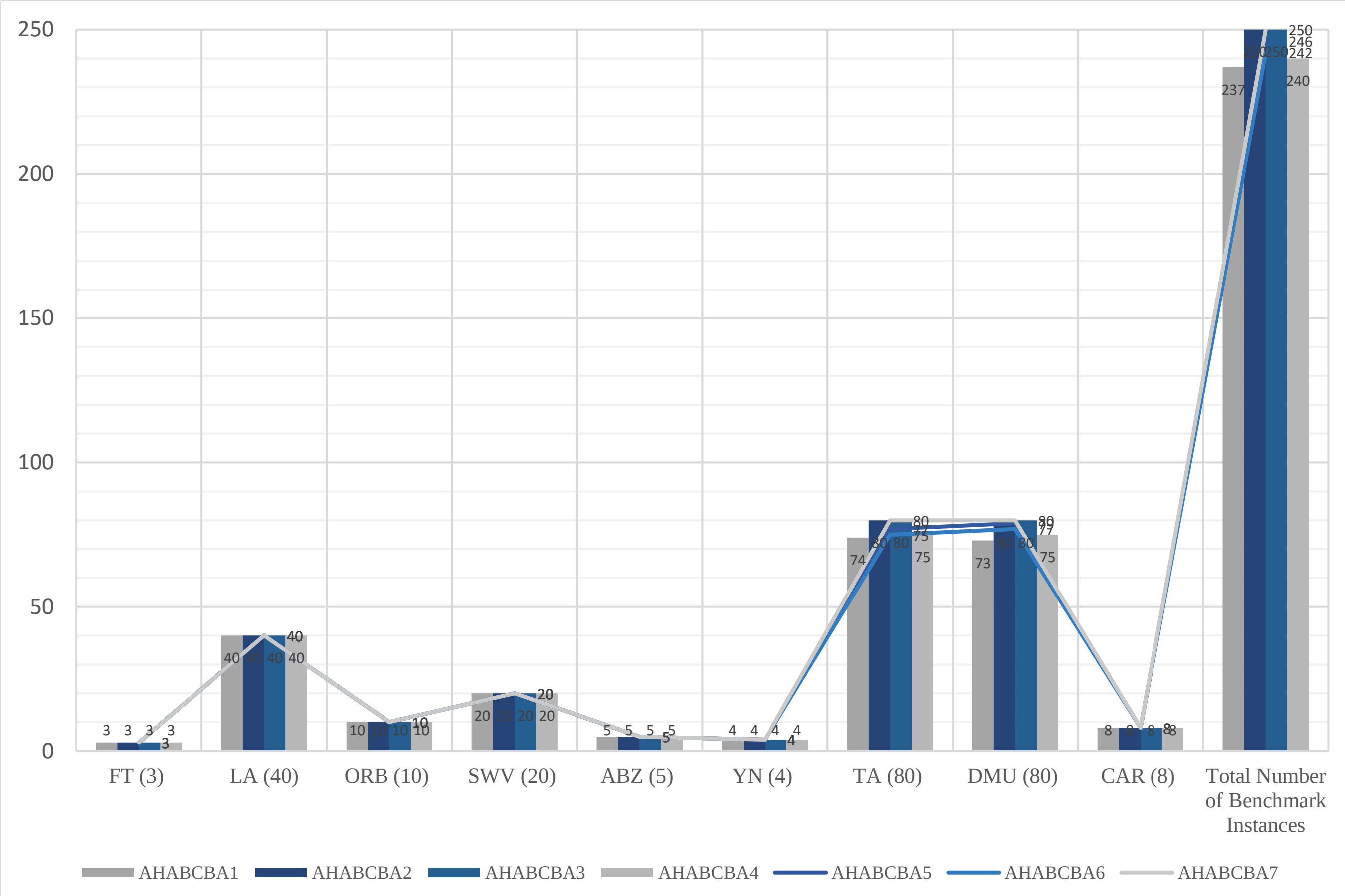


Fig. 5 The performances comparative of the proposed methods AHABCBA

The performances comparative of AHABCBA, based on the hybridization number, is found in Figure 5.

As can be seen in Figure 5 shown above:

1. The results of AHABCBA hybridized in its three phases are equal to the result of AHABCBA hybridized in its onlooker bee and employed bee phase.
2. The results of AHABCBA hybridized in its three phases are equal to the result of AHABCBA hybridized in its scout bee and employed bee phase.
3. The results of AHABCBA hybridized in its onlooker bee and employed bee phase is equal to the result of AHABCBA hybridized in its scout bee and employed bee phase.
4. The AHABCBA hybridized in its two phases provided better results than the AHABCBA hybridized in its one phase.
5. The AHABCBA hybridized in its onlooker bee, and employed bee phase provided better results than the AHABCBA hybridized in its scout bee and onlooker bee phase.
6. The AHABCBA hybridized in its scout bee, and employed bee phase provided better results than the AHABCBA hybridized in its scout bee and onlooker bee phase.
7. The AHABCBA hybridized in its scout bee phase provided better results than the AHABCBA hybridized in its onlooker bee phase or employed bee phase.
8. The AHABCBA hybridized in its onlooker bee phase provided better results than the AHABCBA hybridized in its employed bee phase.

The performances comparative of HABCBA with AHABCBA, based on the hybridization number, is demonstrated in Figure 6.

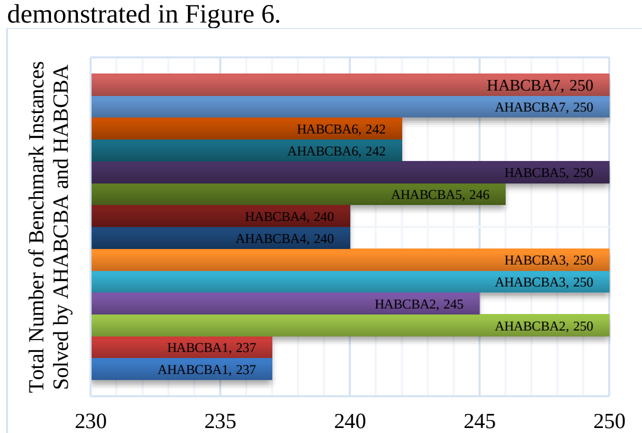


Fig. 6 The performances comparative of HABCBA with AHABCBA

From Figure 6 shown above, one can draw the conclusion that:

1. The HABCBA hybridized in all its phases provided the same results as AHABCBA hybridized in all its phases.
2. The HABCBA hybridized in its scout bee and employed bee phase provided the same results as the AHABCBA hybridized in its scout bee and employed bee phase.
3. The HABCBA hybridized in its scout bee and onlooker bee phase provided better results than the AHABCBA hybridized in its scout bee and onlooker bee phase.
4. The AHABCBA hybridized in its onlooker bee and employed bee phase provided better results than the HABCBA hybridized in its onlooker bee and employed bee phase.
5. The HABCBA hybridized in its scout bee phase provided similar results as the AHABCBA hybridized in its scout bee phase.
6. The HABCBA hybridized in its onlooker bee phase provided similar results as the AHABCBA hybridized in its onlooker bee phase.
7. The HABCBA hybridized in its employed bee phase provided similar results as the AHABCBA hybridized in its employed bee phase.
8. The HABCBA and AHABCBA hybridized in its scout bee phase provided better results than the HABCBA, and AHABCBA hybridized in its onlooker bee phase.
9. The HABCBA and AHABCBA hybridized in its scout bee phase provided better results than the HABCBA, and AHABCBA hybridized in its employed bee phase.
10. The HABCBA and AHABCBA hybridized in its onlooker bee phase provided better results than the HABCBA, and AHABCBA hybridized in its employed bee phase.
11. The HABCBA and AHABCBA hybridized in its two phases provided better results than the HABCBA, and AHABCBA hybridized in its one phase.

The experiment results demonstrated that the HABCBA and AHABCBA had achieved high performance and provided better results than others methods in all reference instances. A thorough evaluation with other approaches, HABCACO [29], HABCPSOGA [31], and HABCGA [32], existing in the literature is performed to validate and compare the reliability and efficacy of the HABCBA and AHABCBA. The comparative study is described in Table 3.

From Table 3, it can be summarized that:

1. The methods HABCBA and AHABCBA hybridized in all their phases are provided with the same results as the methods HABCACO, HABCGA, and HABCPSOGA hybridized in all their phases.
2. The methods HABCBA, AHABCBA, HABCACO, HABCGA, and HABCPSOGA hybridized in its three phases always provide the best results.
3. The methods HABCBA and AHABCBA hybridized in its scout bee and employed bee phase provided better results than the methods HABCACO, HABCGA, and HABCPSOGA hybridized in its employed bee and scout bee phase.
4. The method HABCBA hybridized in its scout bee and onlooker bee phase provided better results than the methods HABCACO, HABCGA, and HABCPSOGA hybridized in its onlooker bee and scout bee phase.
5. The method AHABCBA hybridized in its onlooker bee and employed bee phase provided better results than the methods HABCACO, HABCGA, and HABCPSOGA hybridized in its onlooker bee and employed bee phase.
6. The methods HABCBA and AHABCBA hybridized in its two phases provided better results than the methods HABCACO, and HABCGA hybridized in only one phase.
7. The methods HABCBA and AHABCBA hybridized in its scout bee and employed bee phase provides similar results as the methods HABCACO, HABCGA, and HABCPSOGA hybridized in all its phases.
8. The method HABCBA hybridized in its scout bee and onlooker bee phase provided similar results as the methods HABCACO, HABCGA, and HABCPSOGA hybridized in all its phases.
9. The method AHABCBA hybridized in its onlooker bee, and employed bee phase provided similar results as the methods HABCACO, HABCGA, and HABCPSOGA hybridized in its three phases.
10. The method AHABCBA hybridized in its scout bee and onlooker bee phase provided similar results as the methods HABCACO hybridized in its scout bee and onlooker bee phase.
11. The method AHABCBA hybridized in its scout bee and onlooker bee phase provided similar results as the methods HABCPSOGA and HABCGA hybridized in its employed bee and scout bee phase.
12. The method HABCBA hybridized in its onlooker bee and employed bee phase provides similar results to the methods HABCACO hybridized in its onlooker bee and employed bee phase.
13. The methods HABCBA and AHABCBA hybridized in the scout bee phase provided similar results as the methods HABCACO hybridized in its scout bee phase.
14. The methods HABCBA and AHABCBA hybridized in the scout bee phase provided better results than the methods HABCGA hybridized in its scout bee phase.
15. The methods HABCBA and AHABCBA hybridized in the scout bee phase provided better results than the methods HABCACO and HABCGA hybridized in the onlooker bee phase.
16. The methods HABCBA and AHABCBA hybridized in the scout bee phase provided better results than the methods HABCACO, and HABCGA hybridized in the employed bee phase.
17. The methods HABCBA and AHABCBA hybridized in the onlooker bee phase provided similar results as the

methods HABCACO hybridized in the onlooker bee phase.

18. The methods HABCBA and AHABCBA hybridized in the onlooker bee phase provided better results than the methods HABCGA hybridized in the same phase (onlooker bee phase).
19. The methods HABCBA and AHABCBA hybridized in the onlooker bee phase provided better results than the methods HABCACO, and HABCGA hybridized in the employed bee phase.
20. The methods HABCBA and AHABCBA hybridized in the onlooker bee phase provided better results than the methods HABCGA hybridized in the scout bee phase.
21. The methods HABCBA and AHABCBA hybridized in the employed bee phase provide similar results to those HABCACO hybridized in the employed bee phase.
22. The methods HABCBA and AHABCBA hybridized in the employed bee phase provided better results than the methods HABCGA hybridized in the onlooker bee phase.

The experimental results confirmed that the suggested HABCBA and AHABCBA methods achieved greater precision and efficacy than the existing hybrid methods and have been highly effective in solving job shop scheduling problems. The study's primary limitation is that it focused only on reducing the total time needed to complete all the jobs at C_{max}.

Table 3. The Comparative Study of the HABCBA and AHABCBA With Other Methods

	Employed bee phase	Onlooker bee phase	Scout bee phase	Hybridation number	% Benchmark Instances Solved	Ranking
HABCBA3	BA	BA	BA	3	100,00%	1
HABCBA5		BA	BA	2	100,00%	1
HABCBA7	BA		BA	2	100,00%	1
AHABCBA2	BA	BA		2	100,00%	1
AHABCBA3	BA	BA	BA	3	100,00%	1
AHABCBA7	BA		BA	2	100,00%	1
HABCPSOGA2	GA	GA	PSO	3	100,00%	1
HABCGA3	GA	GA	GA	3	100,00%	1
HABCACO3	ACO	ACO	ACO	3	100,00%	1
HABCPSOGA6	GA	PSO	GA	3	100,00%	1
HABCPSOGA9	PSO	GA	GA	3	100,00%	1
HABCGA2	GA	GA		2	99,80%	2
HABCPSOGA3	GA		PSO	2	99,20%	3
HABCACO7	ACO		ACO	2	99,20%	3
HABCPSOGA7	PSO	GA		2	98,48%	4
AHABCBA5		BA	BA	2	98,40%	5
HABCGA7	GA		GA	2	98,40%	5
HABCPSOGA8	PSO		GA	2	98,40%	5
HABCACO5		ACO	ACO	2	98,40%	5
HABCACO2	ACO	ACO		2	98,00%	6
HABCBA2	BA	BA		2	98,00%	6
HABCPSOGA1		GA	PSO	2	97,90%	7
HABCPSOGA5		PSO	GA	2	97,85%	8
HABCPSOGA4	GA	PSO		2	97,50%	9
HABCGA5		GA	GA	2	96,93%	10
HABCBA6			BA	1	96,80%	11
AHABCBA6			BA	1	96,80%	11
HABCACO6			ACO	1	96,80%	11
HABCACO4		ACO		1	96,00%	12
HABCBA4		BA		1	96,00%	12
AHABCBA4		BA		1	96,00%	12
HABCGA1	GA			1	95,48%	13
HABCGA6			GA	1	95,35%	14
HABCACO1	ACO			1	94,80%	15
HABCBA1	BA			1	94,80%	15
AHABCBA1	BA			1	94,80%	15
HABCGA4		GA		1	94,03%	16

5. Conclusion

Nature-inspired optimization methods have been demonstrated to be very successful in solving many difficult optimization issues in different fields, but there are still a few challenging problems. The researchers dig deeply into hybrid nature-inspired optimization methods to get more efficient solutions for NP-difficult problems.

Job shop scheduling problems are difficult to solve due to their NP-Hard complexity; solving these kinds of problems makes manufacturing companies more competitive. Advanced and powerful hybrid nature-inspired optimization methods are required for maximum efficiency in solving job shop scheduling problems.

In this article, the authors have developed novel, nature-inspired, multi-hybrid methods known as HABCBA and AHABCBA. They are established based on the hybridization of ABC and BA in different ways to produce optimum or near-optimum solutions to job-shop scheduling issues. These advanced methods combine the advantages of the ABC and the BA and perform their efficiency by balancing the exploration and the exploitation activities in order to find the optimal solution and overcome the drawbacks of the ABC and the BA.

The proposed methods are reviewed to assess their performances and effectiveness using all well-known reference instances of the classical OR library. The experimental findings have revealed that the HABCBA and AHABCBA provided good results in all well-known reference instances and demonstrated satisfactory exploration, exploitation, and convergence features.

An extensive comparison with other HABCACO, HABCPSOGA, and HABCGA approaches existing in the literature is conducted to validate and compare the reliability and efficiency of the HABCBA and AHABCBA. The comparative study has shown that the proposed advanced hybrid methods provided better results than the HABCACO, HABCPSOGA, and HABCGA in terms of the total number of efficiently resolved reference instances and the quality of the results. The advanced hybrid methods HABCBA and AHABCBA were more efficient and powerful than these hybrid approaches accessible in the literature.

The authors plan to develop new intelligent and robust hybrid methods for solving NP-Hard problems as part of future research.

Acknowledgments

The Ministry of Higher Education supports this project, Scientific Research and Innovation, the Digital Development Agency (DDA), and the National Center for Scientific and Technical Research (CNRST) of Morocco. APIAA-2019-KAMAL.REKLAOUI-FSTT-Tanger-UAE.

References

[1] Li Xixing, and Liu Yi, "Approach of Solving Dual Resource Constrained Multi-Objective Flexible Job Shop Scheduling Problem Based on MOEA/D," *International Journal of Online and Biomedical Engineering*, vol. 14, no. 7, pp. 75–89, 2018. [CrossRef] [Google Scholar] [Publisher link]

[2] Michael R. Garey, and David S. Johnson, "A Guide to the Theory of NP-Completeness," *Computers and Intractability*, Freeman, 1979. [Publisher link]

[3] H. Fisher, and G.L. Thompson, *Industrial Scheduling*, Englewood Cliffs, NJ: Prentice-Hall, 1963.

[4] S. Lawrence, "*Resource Constrained Project Scheduling: An Experimental Investigation of Heuristic Scheduling Techniques*," Pittsburgh: Graduate School of Industrial Administration, 1984.

[5] Joseph Adams, Egon Balas, and Daniel Zawack, "The Shifting Bottleneck Procedure for Job-Shop Scheduling," *Management Science*, vol. 34, no. 3, pp. 391–401, 1988. [CrossRef] [Google Scholar] [Publisher link]

[6] David Applegate, and William Cook, "A Computational Study of the Job-Shop Scheduling Problem," *ORSA Journal on Computing*, vol. 3, no. 2, pp. 149–156, 1991. [CrossRef] [Google Scholar] [Publisher link]

[7] Takeshi Yamada, and Ryohei Nakano, "A Genetic Algorithm Applicable to Large-Scale Job-Shop Problems," *Proceedings of the second International Workshop on Parallel Problem Solving from Nature (PPSN'2), Brussels, Belgium*, pp. 281–290, 1992. [Google Scholar] [Publisher link]

[8] Robert H. Storer, S. David Wu, and Renzo Vaccari, "New Search Spaces for Sequencing Problems with Application to Job Shop Scheduling," *Management Science*, vol. 38, no. 10, pp. 1495–1509, 1992. [CrossRef] [Google Scholar] [Publisher link]

[9] Éric D. Taillard, "Parallel Taboo Search Techniques for the Job Shop Scheduling Problem," *ORSA Journal on Computing*, vol. 6, no. 2, pp. 108–117, 1994. [CrossRef] [Google Scholar] [Publisher link]

[10] Ebru Demirkol, Sanjay Mehta, and Reha Uzsoy, "A Computational Study of Shifting Bottleneck Procedures for Shop Scheduling Problems," *Journal of Heuristics*, vol. 3, no. 2, pp. 111–137, 1997. [CrossRef] [Google Scholar] [Publisher link]

[11] E.G. Talbi, "A Taxonomy of Hybrid Metaheuristics," *International Journal of Heuristics*, vol. 8, no. 5, pp. 541–564, 2002. [CrossRef] [Google Scholar] [Publisher link]

[12] Thi-Kien Dao et al., "Parallel Bat Algorithm for Optimizing Makespan in Job Shop Scheduling Problems," *Journal of Intelligent Manufacturing*, vol. 29, no. 2, pp. 451–462, 2018. [CrossRef] [Google Scholar] [Publisher link]

[13] Mohamed Kurdi, "A New Hybrid Island Model Genetic Algorithm for Job Shop Scheduling Problem," *Computers & Industrial Engineering*, vol. 88, pp. 273–283, 2015. [CrossRef] [Google Scholar] [Publisher link]

[14] T.C.E. Cheng, Bo Peng, and Zhipeng Lü, "A Hybrid Evolutionary Algorithm to Solve the Job Shop Scheduling Problem," *Annals of Operations Research*, vol. 242, no. 2, pp. 223–237, 2016. [CrossRef] [Google Scholar] [Publisher link]

[15] Andr´e Henning, "*Praktische Job-Shop Scheduling-Probleme*," Ph.D. Thesis, Friedrich-Schiller-Universität Jena, Jena, Germany, 2002. [Publisher link]

[16] José Fernando Gonçalves, and Mauricio G. C. Resende, "An Extended Akers Graphical Method with a Biased Random-Key Genetic Algorithm for Job-Shop Scheduling," *International Transactions on Operational Research*, vol. 21, no. 2, pp. 215–246, 2014. [CrossRef] [Google Scholar] [Publisher link]

[17] Eugeniusz Nowicki, and Czesław Smutnicki, "An Advanced Taboo Search Algorithm for the Job Shop Problem," *Journal of Scheduling*, vol. 8, no. 2, pp. 145–159, 2005. [CrossRef] [Google Scholar] [Publisher link]

[18] Eugeniusz Nowicki, and Czeslaw Smutnicki, "A Fast Taboo Search Algorithm for the Job Shop Problem," *Management Science*, vol. 42, no. 6, pp. 783–938, 1996. [CrossRef] [Google Scholar] [Publisher link]

[19] Marco Antonio Cruz-Chávez et al., "Hybrid Micro Genetic Multi-Population Algorithm with Collective Communication for the Job Shop Scheduling Problem," *IEEE Access*, vol. 7, pp. 82358–82376, 2019. [CrossRef] [Google Scholar] [Publisher link]

[20] Bao-An Han, and Jian-Jun Yang, "Research on Adaptive Job Shop Scheduling Problems Based on Dueling Double DQN," *IEEE Access*, vol. 8, pp. 186474–186495, 2020. [CrossRef] [Google Scholar] [Publisher link]

[21] Panos M. Pardalos, Oleg V. Shylo, and Alkis Vazacopoulos, "Solving Job Shop Scheduling Problems Utilizing the Properties of Backbone and Big Valley," *Computational Optimization and Applications*, vol. 47, no. 1, pp. 61–76, 2010. [CrossRef] [Google Scholar] [Publisher link]

[22] Ferdinando Pezzella, and Emanuela Merelli, "A Tabu Search Method Guided by Shifting Bottleneck for the Job Shop Scheduling Problem," *European Journal of Operational Research*, vol. 120, no. 2, pp. 297–310, 2000. [CrossRef] [Google Scholar] [Publisher link]

[23] Petr Vil´ım, Philippe Laborie, and Paul Shaw, "Failure-Directed Search for Constraint-Based Scheduling-Detailed Experimental Results," *CPAIOR'2015, Barcelona, Spain*, pp. 437–453, 2015. [Google Scholar] [Publisher link]

[24] Bo Peng, Zhipeng Lü, and T.C.E. Cheng, "A Tabu Search/Path Relinking Algorithm To Solve The Job Shop Scheduling Problem," *Computers and Operations Research*, vol. 53, pp. 154–164, 2015. [CrossRef] [Google Scholar] [Publisher link]

[25] Oleg V. Shylo, and Hesam Shams, "Boosting Binary Optimization via Binary Classification: A Case Study of Job Shop Scheduling," *cs.AI/math.OC abs/1808.10813, arXiv*, 2018. [CrossRef] [Google Scholar] [Publisher link]

[26] Shao-Juan Wang, Chun-Wei Tsai, and Ming-Chao Chiang, "A High Performance Search Algorithm for Job-Shop Scheduling Problem," *Procedia Computer Science*, vol. 141, pp. 119–126, 2018. [CrossRef] [Google Scholar] [Publisher link]

[27] Leila Asadzadeh, "A Local Search Genetic Algorithm for the Job Shop Scheduling Problem with Intelligent Agents," *Computers & Industrial Engineering*, vol. 85, pp. 376–383, 2015. [CrossRef] [Google Scholar] [Publisher link]

[28] S.K. Sahana, I. Mukherjee, and P.K. Mahanti, "Parallel Artificial Bee Colony (PABC) for Job Shop Scheduling Problems," *Advances in Information Sciences and Service Sciences*, vol. 10, no. 3, pp. 1–11, 2018.

[29] Jebari Hakim, Siham Rekiek, and Kamal Reklaoui, "Solving the Job Shop Scheduling Problem by the Multi-Hybridization of Swarm Intelligence Techniques," *International Journal of Advanced Computer Science and Applications*, vol. 13, no. 7, pp. 753–764, 2022. [CrossRef] [Google Scholar] [Publisher link]

[30] S. Sivasubramaniam, and S.P. Balamurugan, "Nature Inspired Optimization with Hybrid Machine Learning Model for Cardiovascular Disease Detection and Classification," *International Journal of Engineering Trends and Technology*, vol. 70, no. 12, pp. 127–137, 2022. [CrossRef] [Publisher link]

[31] Jebari Hakim et al., "Multi Hybridization of Swarm Intelligence Methods to Solve Job Shop Scheduling Problem," *Journal of Theoretical and Applied Information Technology*, vol. 97, no. 16, pp. 4366–4386, 2019. [Google Scholar] [Publisher link]

[32] Jebari Hakim et al., "The Search of Balance Between Diversification and Intensification in Artificial Bee Colony to Solve Job Shop Scheduling Problem," *Journal of Theoretical and Applied Information Technology*, vol. 97, no. 2, pp. 658–673, 2019. [Google Scholar] [Publisher link]

[33] Dervis Karaboga, "*An Idea Based on Honey Bee Swarm for Numerical Optimization*," Technical Report-TR06, Erciyes University, Engineering Faculty, Computer Engineering Department, vol. 200, 2005. [Google Scholar] [Publisher link]

[34] D. Karaboga, and B. Akay, "A Comparative Study of Artificial Bee Colony Algorithm," *Applied Mathematics and Computation*, vol. 214, no. 1, pp. 108–32, 2009. [CrossRef] [Google Scholar] [Publisher link]

[35] V. Satyanarayana and V. Jayasankar, "Advanced Modeling and Optimization of Hybrid Renewable Energy Management Strategy Based on Artificial Bee Colony Algorithm in Micro Grid," *International Journal of Engineering Trends and Technology*, vol. 70, no. 10, pp. 329–338, 2022. [CrossRef] [Publisher link]

[36] Ammar K Alazzawi, Helmi Md Rais, and Shuib Basri, "ABCVS: An Artificial Bee Colony for Generating Variable T-Way Test Sets," *International Journal of Advanced Computer Science and Applications*, vol. 10, no. 4, pp. 259–274, 2019. [CrossRef] [Google Scholar] [Publisher link]

[37] M. Fatih Tasgetiren et al., "A Discrete Artificial Bee Colony Algorithm for the Total Flowtime Minimization in Permutation Flow Shops," *Information Sciences*, vol. 181, no. 16, pp. 3459–3475, 2011. [CrossRef] [Google Scholar] [Publisher link]

[38] Nasser Tairan, Habib Shah, and Aliya Aleryani, "Prediction of Crude Oil Prices Using Hybrid Guided Best-So-Far Honey Bees Algorithm-Neural Networks," *International Journal of Advanced Computer Science and Applications*, vol. 10, no. 5, pp. 317–330, 2019. [CrossRef] [Google Scholar] [Publisher link]

[39] S. Sivasubramaniam, and S. P. Balamurugan, "Nature Inspired Optimization with Hybrid Machine Learning Model for Cardiovascular Disease Detection and Classification," *International Journal of Engineering Trends and Technology*, vol. 70, no. 12, pp. 127-137, 2022. [CrossRef] [Publisher link]

[40] Shyam Sunder Pabboju, and Adilakshmi Thondepu, "Effective Task Scheduling in Cloud Computing using Improved BAT Algorithm," *International Journal of Engineering Trends and Technology*, vol. 70, no. 10, pp. 271–276, 2022. [CrossRef] [Publisher link]

[41] Xin-She Yang, "Bat Algorithm: Literature Review and Applications," *International Journal of Bio-Inspired Computing*, vol. 5, no. 3, pp. 141–149, 2013. [CrossRef] [Google Scholar] [Publisher link]

[42] Koffka Khan, Alexander Nikov, and Ashok Sahai, "A Fuzzy Bat Clustering Method for Ergonomic Screening of Office Workplaces," *Advances in Intelligent and Soft Computing*, vol. 101, pp. 59–66, 2011. [CrossRef] [Google Scholar] [Publisher link]

[43] Waqas Haider Bangyal et al., "An Improved Bat Algorithm based on Novel Initialization Technique for Global Optimization Problem," *International Journal of Advanced Computer Science and Applications*, vol. 9, no. 7, pp. 158–166, 2018. [CrossRef] [Google Scholar] [Publisher link]

[44] Jiann-Horng Lin et al., "A Chaotic Levy Flight Bat Algorithm for Parameter Estimation in Nonlinear Dynamic Biological Systems," *Journal of Computing and Information Technology*, vol. 2, no. 2, pp. 56–63, 2012. [Google Scholar] [Publisher link]

[45] Jian Xie, Yongquan Zhou, and Huan Chen, "A Novel Bat Algorithm Based on Deferential Operator and Levy Flights Trajectory," *Computational Intelligence and Neuroscience*, pp. 1–13, 2013. [CrossRef] [Google Scholar] [Publisher link]

[46] Caichang Ding, Wenxiu Peng, and Weiming Wang, "Hybrid Metaheuristics and their Implementations," *International Journal of Online and Biomedical Engineering*, vol. 11, no. 7, pp. 25–28, 2015. [CrossRef] [Google Scholar] [Publisher link]

[47] Ramanathan.L, and Ulaganathan.K, "Nature-inspired Metaheuristic Optimization Technique-Migrating Bird‟s Optimization in Industrial Scheduling Problem," *SSRG International Journal of Industrial Engineering*, vol. 1, no. 2, pp. 12-17, 2014. [CrossRef] [Google Scholar] [Publisher link]

[48] Yazhi Li, Xiaoping Li, and Jatinder N.D. Gupta, "Solving the Multi-Objective Flowline Manufacturing Cell Scheduling Problem by Hybrid Harmony Search," *Expert Systems with Applications*, vol. 42, no. 3, pp. 1409-1417, 2015. [CrossRef] [Google Scholar] [Publisher link]

[49] Xiuli Wu, Xianli Shen, and Qi Cui, "Multi-Objective Flexible Flow Shop Scheduling Problem Considering Variable Processing Time due to Renewable Energy," *Sustainability*, vol. 10, no. 3, p. 841, 2018. [CrossRef] [Google Scholar] [Publisher link]

[50] Dervis Karaboga et al., "A Comprehensive Survey: Artificial Bee Colony (Abc) Algorithm and Applications," *Artificial Intelligence Review*, vol. 42, no. 1, pp. 21–57, 2014. [CrossRef] [Google Scholar] [Publisher link]

[51] Xin-She Yang, *Nature-Inspired Optimization Algorithms*, Elsevier, London, 2014. [CrossRef] [Google Scholar] [Publisher link]