Performance Comparison of Three Hybridization Categories to Solve Multi-Objective Flow Shop Scheduling Problem

A Case Study from the Automotive Industry

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Abstract—The industries must preserve a rate of constant productivity; however, weaknesses appear at the level of production system which engenders high manufacturing costs. Scheduling is considered the most significant issue in the production system, the solution to that problem need complex methods to solve it. The goal of this paper is to establish three hybridization categories of the evolutionary methods ABC and PSO to solve multi-objective flow shop scheduling problem: Synchronous parallel hybridization using the weighted sum method of the fitness function, sequential hybridization using or not using the weighted sum method of the fitness function, and asynchronous parallel hybridization using the weighted sum method of the fitness function. Then to test these methods in an automotive multi-objective flow shop and to perform an in-depth comparison for verifying how the multi hybridization and the hybridization categories influence the resolution of multi-objective flow shop scheduling problems. The results are consistent with other studies that have shown that the multi hybridization improve the effectiveness of the algorithm.

Keywords—Scheduling; multi-objective; flow shop; multi hybridization; artificial bee colony ABC; particle swarm optimization PSO

I. INTRODUCTION

The objectives of companies are diversified and the scheduling became multi-criterion. The scheduling objective are related to the time or the resources or the cost.

The scheduling problem in the production system is a accomplishment of a tasks group by taking in consideration some constraints.

The hybrid metaheuristics are proposed by Talbi [1] and are classified in three classification [2]:

• Synchronous parallel hybridization consists of incorporating an approach in an operator of another approach.

• Sequential hybridization is composed by various approaches, the solution of the first approach is an initialization of the next approach.

• Asynchronous parallel hybridization, the hybrid approaches share data throughout the search process.

In the flow shop scheduling problem, every machine can make only a single operation simultaneously and every job can have just a single operation in progress at the same instant. The capacity of storage inter-machines is defined and the preemption of operations is not approved.

Solving multi-objective flow shop scheduling problem has been gaining importance in recent years, in fact, many authors have developed diverse hybrid approaches and not hybrid approaches : Genetic local search [3], artificial neural network [4], particle swarm optimization [5], ant colony system [6], GRASP heuristic [7], hybrid TP+PLS [8], pareto approach [9], [10], [11], [12], multi-objective genetic algorithm and sub-population genetic algorithm-II and non-dominated sorting genetic algorithm-II [13], multi-objective genetic algorithm [14], quantum differential evolutionary algorithm [15], Parallel multiple reference point approach [16], glowworm swarm optimization [17], genetic algorithm [18], genetic algorithm optimization technique [19], memetic algorithm [20], hybrid non-dominated sorting genetic algorithm with variable local search [21], hybrid harmony search [22], Heuristic algorithms [23], lower-bound-based GA [24]. [25] summarizes some contributions to solve flow shop scheduling problem.

However, to the authors’ knowledge, very few publications are available in the literature that performed an in-depth comparison for verifying how the multi hybridization and the hybridization categories influence the resolution of multi-objective flow shop scheduling problem.

The objective of this paper is as follows:

• To establish three hybridization categories of the evolutionary methods ABC and PSO to solve multi-objective flow shop scheduling problem: Synchronous parallel hybridization using the weighted sum method of the fitness function, sequential hybridization using or not using the weighted sum method of the fitness function, and asynchronous parallel hybridization using the weighted sum method of the fitness function.
The artificial bee colony ABC algorithm is one of the most newly added swarm-based algorithms. ABC method created by Karaboga, it was copied the intelligent foraging behavior observed in the domestic bees to take the process of foraging [26].

ABC technique was produced for optimization problems in the continuous field. Recently, it was further enlarged for optimization problems in the discrete area [27] [28] [29] [30] [31].

A complete review of the utilization of ABC algorithm can be found in [32].

Four phases make ABC: Initialization bee phase, employed bees phase associate with particular food sources, onlooker bees phase look at the dance of engaged bees within the hive to choose a food source, and scout bees phase search randomly food sources.

In the ABC algorithm, the position of a food source corresponds to a possible feasible solution to the studied problem, and the nectar amount of a food source design the fitness of the solution.

The ABC algorithm merges techniques of local search and global search, trying to balance between the exploration and the exploitation of the search zone.

The main steps of the ABC method are as follows:

<table>
<thead>
<tr>
<th>Initialization Phase (Initialize Population)</th>
</tr>
</thead>
<tbody>
<tr>
<td>REPEAT</td>
</tr>
<tr>
<td>Employed Bees Phase (Put the employed bees on their food sources)</td>
</tr>
<tr>
<td>Onlooker Bees Phase (Put the onlooker bees on the food sources according to their nectar amounts)</td>
</tr>
<tr>
<td>Scout Bees Phase (Send the scouts to the search zone for exploring new food sources)</td>
</tr>
<tr>
<td>Record the best food source attained so far</td>
</tr>
</tbody>
</table>

| Until requirements are met |

B. Fundamentals of Particle Swarm Optimization

Particle Swarm Optimization PSO technique is a popular swarm-intelligence-based algorithm that optimizes a problem using an approach that is motivated by the movements of schooling of fishes or a flock of birds.

It was founded by Eberhart and Kennedy in 1995 [33] and has received significant attention from researchers studying in several research fields and has been successfully employed to many optimization problems since then [34] [35] [36].

The candidate solutions of a studied problem are designed as particles that form a population. The location of each particle is determined with two swarm main characteristics: the particle’s position and velocity. The position of a particle represents a specific solution to the studied problem, while velocity is employed to define the direction of the particle in the next iteration.

Two reference values manage the movement of a particle throughout the iterations: The best fitness value obtained by the particle and the best fitness value of the swarm registered so far. The PSO has a memory that deposits the best fitness value of all particles achieved so far, and the corresponding position.

Applying these principles, improvement is accomplished and the PSO is conducted to the optimal solution.

The main steps of PSO are as follows:

| Randomly generate the initial population and the velocities |
| Repeat |
| Determine the best values of particles in the swarm |
| Change the best particles in the swarm |
| Determine the best particle |
| Update the velocities of particles |
| Update the particle position |
| Until requirements are met |

C. The Proposed Methods

The ABC has a high capacity to explore the global optimum who it is not immediately employed, because the ABC stocks it at each iteration, on the other hand, the PSO can immediately employ the global best solution at iteration.

To obtain a better-performing method that exploits and combines advantages of these algorithms, the proposed hybridization between the ABC and PSO is applied.

The proposed hybrid metaheuristics are developed in three-hybridization categories: Synchronous parallel hybridization, sequential hybridization and asynchronous parallel hybridization.

1) Synchronous parallel multiple hybridization of ABC with PSO: The authors developed a new approach of synchronous parallel hybridization of ABC and PSO called HABCPSO. This approach consists to employ in the employed bees phase or/and in the onlooker bees phase or/and in the scout bees phase, the position and the velocity updating process, the Table I shown the configuration of the HABCPSO methods.

Consequently, the procedure of HABCPSO2 and HABCPSO3 can be found in Fig. 1 and Fig. 2 respectively.
The fitness function $F$ minimized in HABCPSO corresponds to the balanced sum of both objectives functions $F_1$ and $F_2$, with weights $\beta_1$ and $\beta_2$ defined as follows:

$$F = F_1 \beta_1 + F_2 \beta_2, \beta_1 + \beta_2 = 1, \beta_1 > 0, \beta_2 > 0$$

(1)

1) Sequential hybridization of ABC with PSO: The proposed hybrid methods, denoted as [ABC+PSO](F) and ABC(F1)+PSO(F2), are founded on the recombination of two procedures ABC and PSO. The PSO is applied after the ABC.

PSO has used the output of the previous as its inputs, there are acting in a pipeline way.

The procedures of [ABC+PSO](F) and ABC(F1)+PSO(F2) are illustrated in Fig. 3.

The fitness function $F$ minimized in [ABC+PSO](F) corresponds to the balanced sum of both objectives functions $F_1$ and $F_2$, with weights $\beta_1$ and $\beta_2$ defined by the function 1.

The fitness functions $F_1/F_2$ minimized in ABC(F1)+PSO(F2) corresponds to objective function $F_1$ minimized in ABC(F1) and objective function $F_2$ minimized in PSO(F2).

2) Sequential hybridization of PSO with ABC: The proposed hybrid methods denoted as [PSO+ABC](F) and PSO(F1)+ABC(F2) are founded on the recombination of two procedures ABC and PSO. The ABC is applied after the PSO.

ABC has used the output of the previous as its inputs, there are acting in a pipeline way.

The procedures of [PSO+ABC](F) and PSO(F1)+ABC(F2) are illustrated in Fig. 4.

### TABLE I. THE CONFIGURATION OF THE HABCPSO METHODS

<table>
<thead>
<tr>
<th>Hybrid ABC + PSO</th>
<th>Employed bee phase</th>
<th>Onlooker bee phase</th>
<th>Scout bee phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>HABCPSO1</td>
<td>position and velocity updation process</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HABCPSO2</td>
<td>position and velocity updation process</td>
<td>position and velocity updation process</td>
<td></td>
</tr>
<tr>
<td>HABCPSO3</td>
<td>position and velocity updation process</td>
<td>position and velocity updation process</td>
<td>position and velocity updation process</td>
</tr>
<tr>
<td>HABCPSO4</td>
<td>position and velocity updation process</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HABCPSO5</td>
<td>position and velocity updation process</td>
<td>position and velocity updation process</td>
<td></td>
</tr>
<tr>
<td>HABCPSO6</td>
<td>position and velocity updation process</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HABCPSO7</td>
<td>position and velocity updation process</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 1. The Procedure of HABCPSO2.

The fitness function $F$ minimized in [PSO+ABC](F) corresponds to the balanced sum of both objectives functions $F_1$ and $F_2$, with weights $\beta_1$ and $\beta_2$ defined by the function 1.

The fitness functions $F_1/F_2$ minimized in PSO(F1)+ABC(F2) corresponds to objective function $F_1$ minimized in PSO(F1) and objective function $F_2$ minimized in ABC(F2).

3) Asynchronous parallel hybridization of ABC with PSO: The proposed hybrid method denoted as ABC//PSO is founded on the recombination of two procedures ABC and PSO, this share and exchange information throughout the search process. The procedures of ABC//PSO algorithm are illustrated in Fig. 5.

The fitness function $F$ minimized in ABC//PSO corresponds to the balanced sum of both objectives functions $F_1$ and $F_2$, with weights $\beta_1$ and $\beta_2$ defined by the function 1.
Authors are suggested to solve the multi-objective scheduling problem in the automotive company. This company produces automotive parts in different elastomeric materials, including silicone and TPE.

The automotive company workshop is a flow shop contains 17 production lines, each line is composed with seven workstations:

- M1: The injection machine.
- M2: The deburring workstation.
- M3: The inspection workstation.
- M4: The assembly workstation number 1.
- M5: The assembly workstation number 2.
- M6: The color control machine.
- M7: The inspection workstation of the finished product.

The real result of scheduling obtained from the production planner is shown in Table II.
Several operations of cleaning and tools change or parameter adjustment are managed in the workstations, parallelly with the production operations. Dates are calculated from an initial time $t_0$, and the time unit is expressed in minute.

The fitness function of total production cost is denoted $F_1$ and the fitness function of the stopping cost and the cost of not-use of the production line are denoted $F_2$.

The fitness function $F_1$ and $F_2$ are given as follows:

$$F_1 = C_{\text{prod}}^{\text{tot}} = \sum_k \sum_i W_{ik} P_{ik} C_{ui}^k$$

(2)

$$W_{ik} = \begin{cases} 1 & \text{If the product is maked in the production line} \\ 0 & \text{Otherwise} \end{cases}$$

The fitness function $F_2$ is given as follows:

$$F_2 = C_{\text{arr}}^{\text{tot}} = \sum_k C_{\text{arr}}^k \sum_i W_{ik} \ t_{pi}^{arr} + \ t_{pi}^{nu} \ \text{tel que} \ t_{pi}^{arr} = D_{ik}^{\text{nett}} + D_{ik}^{\text{chf}}$$

(3)

$$W_{ik} = \begin{cases} 1 & \text{If the product is maked in the production line} \\ 0 & \text{Otherwise} \end{cases}$$

Consequently, the fitness function $F$ is given as follows:

$$F = F_1 \beta_1 + F_2 \beta_2 \ , \ \beta_1 + \beta_2 = 1, \beta_1 > 0, \beta_2 > 0$$

(4)

$$F = \beta_1 C_{\text{prod}}^{\text{tot}} + \beta_2 C_{\text{arr}}^{\text{tot}} , \beta_1 + \beta_2 = 1, \beta_1 > 0, \beta_2 > 0$$

(5)

$$F = \beta_1 (\sum_k \sum_i W_{ik} P_{ik} C_{ui}^k) + \beta_2 (\sum_k C_{\text{arr}}^k \sum_i W_{ik} \ t_{pi}^{arr} + \ t_{pi}^{nu})$$

(6)

$$\beta_1 + \beta_2 = 1, \beta_1 > 0, \beta_2 > 0$$

The value considered for factors $\beta_1$ and $\beta_2$ is 0.5.

- $F_{ik}$: Manufacturing operation of the product $i$ in the production line $Ch_k$.
- $P_{ik}$: Finished product after the operation $F_{ik}$.
- $R_{ik}$: Manufacturing time of the operation $F_{ik}$.
- $C_{P_{ik}}$: Time of the end of the execution of $P_{ik}$ in the production line $Ch_k$.
- $C_{P_{ik}}^{\text{st}}$: Storage cost by unit of time of the product $P_{ik}$.
- $t_{pi}^{arr}$: Setup time of the production line $Ch_k$ before the operation $F_{ik}$.
- $t_{pi}^{arr}$: Stopping time during the operation $F_{ik}$ in the line $Ch_k$.
- $t_{pi}^{nu}$: Time of no use of the line $Ch_k$ before the operation $F_{ik}$.
- $C_{\text{prod}}^{\text{tot}}$: Total production cost.
- $C_{ui}^k$: The production unit cost of the product $i$ in the production line $Ch_k$.
- $D_{ik}^{\text{nett}}$: Operations duration of the cleaning in the production line $Ch_k$.
- $D_{ik}^{\text{chf}}$: Changes format duration in the production line $Ch_k$.
- $C_{\text{arr}}^k$: Stopping costs and no use of the production line $Ch_k$ per unit time.
- $C_{\text{tot}}$: Total stopping cost and no use of line by time unit.
- $t_{\text{rop}}_{Ch_k}$: The production time expressed in time unit.
- $t_{\text{arr}}_{Ch_k}$: The stopping time expressed in time unit.
- $t_{\text{nett}}_{Ch_k}$: The cleaning time expressed in time unit.
- $C_{\text{pro}_{Ch_k}}$: Production costs.
- $C_{\text{nou}_{Ch_k}}$: The costs of no use of the production line.

In the employed bees phase; the function of updated memory is as follows [22]:

$$y_{ij} = x_{ij} + \phi_{ij} (x_{ij} + x_{kj}), k \neq i , i = \{1, 2 \ldots , SN\}, j = \{1, 2 \ldots , D\}, \phi_{ij} = Rand [-1, 1]$$

(7)

$x_{\text{min}}$, $x_{\text{max}}$ are respectively the lower and the upper bound of the search scope and $y_{ij}$ is new feasible dimension value of the food sources that is modified from its previous food sources value $x_{ij}$.

In the onlooker bees phase, the probability value related with the food source $(p_i)$ is as follows [22]:

$$p_i = \frac{f_{it}}{\sum_{k=1}^{SN} f_{it_k}}$$

(8)

$f_{it}$ is the fitness value of the solution.

In the scout bees phase, the transmission function is defined as follows [21]:

$$x^{j}_{i} = x^{j}_{\text{min}} + \text{rand} [0,1] (x^{j}_{\text{max}} - x^{j}_{\text{min}})$$

(9)

Each iteration a particle's velocity and a particle's position are updated according to the equation:

$$V_{k+1} = \mu V_k + C_1 \text{rand} (p_{\text{best_{k}}}-\text{current_{k}}) + C_2 \text{rand} (g_{\text{best_{k}}}-\text{current_{k}})$$

(10)

where $\mu$ is the inertia factor and used to control intensification and diversification, $V[]$ is the particle velocity and $C_1/ C_2$ are the apprenticeship factors.

The algorithms were programmed in Java and executed in Core TM i7 CPU with 2.5GHz and 8 Go de RAM.

The ABC stopping criterion defines the maximum number of cycles that a food source can keep without improvement.

The $t_{\text{arr}}_{Ch_k}$ and $t_{\text{nett}}_{Ch_k}$ values of product $i$ in each production line are given as follows:

$$\forall \ i \in \{1, 2, 3, \ldots , 17\} \ t_{\text{arr}}_{Ch_k}(P_i) \in [5,10]$$

$$\forall \ i \in \{1, 2, 3, \ldots , 17\} \ t_{\text{nett}}_{Ch_k}(P_i) \in [5,15]$$

The $t_{\text{rop}}_{Ch_k}$ value of product $i$ in each production line is given as follows:
TABLE II. THE GLOBAL RESULTS OF THE PROPOSED METHODS AND THE REAL RESULTS

<table>
<thead>
<tr>
<th>Number of jobs</th>
<th>Makespan of ABC with PSO</th>
<th>Sequential hybridization of ABC with PSO</th>
<th>Asynchronous parallel hybridization of ABC with PSO</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ABC</td>
<td>PSO</td>
<td>HABCPSO1</td>
</tr>
<tr>
<td>25</td>
<td>512</td>
<td>454</td>
<td>351</td>
</tr>
<tr>
<td>40</td>
<td>591</td>
<td>524</td>
<td>415</td>
</tr>
<tr>
<td>60</td>
<td>679</td>
<td>608</td>
<td>491</td>
</tr>
<tr>
<td>85</td>
<td>783</td>
<td>700</td>
<td>558</td>
</tr>
<tr>
<td>110</td>
<td>832</td>
<td>737</td>
<td>583</td>
</tr>
<tr>
<td>130</td>
<td>865</td>
<td>748</td>
<td>585</td>
</tr>
<tr>
<td>160</td>
<td>901</td>
<td>787</td>
<td>557</td>
</tr>
<tr>
<td>190</td>
<td>936</td>
<td>822</td>
<td>566</td>
</tr>
<tr>
<td>230</td>
<td>1016</td>
<td>878</td>
<td>677</td>
</tr>
<tr>
<td>270</td>
<td>1077</td>
<td>926</td>
<td>715</td>
</tr>
<tr>
<td>310</td>
<td>1103</td>
<td>942</td>
<td>633</td>
</tr>
<tr>
<td>350</td>
<td>1183</td>
<td>1015</td>
<td>771</td>
</tr>
<tr>
<td>400</td>
<td>1246</td>
<td>1071</td>
<td>813</td>
</tr>
<tr>
<td>450</td>
<td>1294</td>
<td>1105</td>
<td>830</td>
</tr>
<tr>
<td>500</td>
<td>1325</td>
<td>1135</td>
<td>851</td>
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<tr>
<td>600</td>
<td>1482</td>
<td>1267</td>
<td>821</td>
</tr>
<tr>
<td>700</td>
<td>1578</td>
<td>1341</td>
<td>995</td>
</tr>
<tr>
<td>800</td>
<td>1686</td>
<td>1428</td>
<td>1058</td>
</tr>
<tr>
<td>900</td>
<td>1795</td>
<td>1516</td>
<td>1118</td>
</tr>
</tbody>
</table>

∀ i = {1, 2, 3, ..., 17} trop_Ch_i(P_i) ∈ [30,90]

The Cpro_Ch_i and Cnou_Ch_i values of product i in each production line are calculated according to formulas 2 and 3 and fitness function deduct from formulas 4 and 5.

The global results of the proposed methods are shown in Table II.

The computational results demonstrate that all proposed methods are given the best results compared with the real results in terms of solution quality.

The results show that the synchronous parallel hybridization method HABCPSO3 is given the best results compared with other results obtained by the sequential hybridization methods and the asynchronous parallel hybridization methods.

The results show that the synchronous parallel hybridization method HABCPSO3 is given the best results compared with other results obtained by the synchronous parallel hybridization methods, the synchronous parallel hybridization method HABCPSO5 is given the equal results to the results obtained by the synchronous parallel hybridization methods HABCPSO6 independent of the hybridization type. These are presented in Fig. 6.

The ranking of the synchronous parallel hybridization methods in terms of performance according to the hybridization type is shown in Table III.

![Fig. 6. The Results of the Synchronous Parallel Hybridization Methods.](image-url)
TABLE III. THE RANKING OF THE SYNCHRONOUS PARALLEL HYBRIDIZATION METHODS

<table>
<thead>
<tr>
<th>Ranking</th>
<th>Synchronous parallel hybridization of ABC and PSO</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>HABCPS O1</td>
</tr>
<tr>
<td>3</td>
<td>HABCPS O2</td>
</tr>
<tr>
<td>1</td>
<td>HABCPS O3</td>
</tr>
<tr>
<td>4</td>
<td>HABCPS O4</td>
</tr>
<tr>
<td>2</td>
<td>HABCPS O5</td>
</tr>
<tr>
<td>2</td>
<td>HABCPS O6</td>
</tr>
<tr>
<td>6</td>
<td>HABCPS O7</td>
</tr>
</tbody>
</table>

Fig. 7 is shown that the sequential hybridization method ABC(F1)+PSO(F2) is given the best results compared with other results obtained by the other sequential hybridization methods.

As shown in Fig. 7:

- The sequential hybridization method [ABC+PSO](F) is given the best results compared with the results obtained by the sequential hybridization method [PSO+ABC](F).
- The sequential hybridization method ABC(F1)+PSO(F2) is given the best results compared with the results obtained by the sequential hybridization method PSO(F1)+ABC(F2).

Fig. 7. The Results of the Sequential Hybridization Methods.

TABLE IV. THE RANKING OF THE SEQUENTIAL HYBRIDIZATION METHODS

<table>
<thead>
<tr>
<th>Ranking</th>
<th>Sequential hybridization of ABC and PSO</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>ABC(F1)+PSO(F2)</td>
</tr>
<tr>
<td>2</td>
<td><a href="F">ABC+PSO</a></td>
</tr>
<tr>
<td>3</td>
<td>PSO(F1)+ABC(F2)</td>
</tr>
<tr>
<td>4</td>
<td><a href="F">PSO+ABC</a></td>
</tr>
</tbody>
</table>

The ranking of the sequential hybridization methods in terms of performance according to the fitness function F or F1 and F2 is shown in Table IV.

The results show that the asynchronous parallel hybridization method ABC//PSO is given the equal results to the results obtained by the sequential hybridization method ABC(F1)+PSO(F2), the asynchronous parallel hybridization method ABC//PSO is given the best results compared with other results obtained by the other sequential hybridization methods [ABC+PSO](F), PSO(F1)+ABC(F2), [PSO+ABC](F).

The ranking of the asynchronous parallel hybridization method and the sequential hybridization methods in terms of performance according to the fitness function F or F1 and F2 is shown in Table V.

As shown in Fig. 8:

- The synchronous parallel hybridization method HABCPSO2 is given the equal results to the results obtained by the sequential hybridization method ABC(F1)+PSO(F2) and the asynchronous parallel hybridization method ABC//PSO.
- The synchronous parallel hybridization HABCPSO4 is given the equal results to the results obtained by the Sequential hybridization [PSO+ABC](F).
- The synchronous parallel hybridization method HABCPSO2, the sequential hybridization method ABC(F1)+PSO(F2) and the asynchronous parallel hybridization method ABC//PSO are given the best results compared with other results obtained by the synchronous parallel hybridization HABCPSO4 and the sequential hybridization [PSO+ABC](F).
- The synchronous hybridization method ABC(F1)+PSO(F2) is given the best results compared with other results obtained by the synchronous hybridization method [PSO+ABC](F).

TABLE V. THE RANKING OF THE ASYNCHRONOUS PARALLEL HYBRIDIZATION METHOD AND THE SEQUENTIAL HYBRIDIZATION METHODS

<table>
<thead>
<tr>
<th>Ranking</th>
<th>Hybrid ABC and PSO</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Asynchronous parallel hybridization of ABC and PSO</td>
</tr>
<tr>
<td>1</td>
<td>Sequential hybridization of ABC and PSO</td>
</tr>
<tr>
<td>2</td>
<td>Sequential hybridization of ABC and PSO</td>
</tr>
<tr>
<td>3</td>
<td>PSO(F1)+ABC(F2)</td>
</tr>
<tr>
<td>4</td>
<td><a href="F">PSO+ABC</a></td>
</tr>
</tbody>
</table>

Fig. 8. The Results of the Asynchronous Parallel Hybridization Method and the Sequential Hybridization Methods.
The results of the synchronous parallel hybridization methods HABCPSO2 / HABCPSO4 and the asynchronous parallel hybridization method ABC//PSO and the sequential hybridization methods ABC(F1)+PSO(F2) / [PSO+ABC](F) in terms of performance according to the fitness function is shown in Table VI.

The ranking of the asynchronous parallel hybridization methods HABCPSO2 / HABCPSO4 and the sequential hybridization methods ABC(F1)+PSO(F2) / [PSO+ABC](F) in terms of performance according to the fitness function is shown in Table VI.

Summing up the results according to the ranking of the proposed methods in terms of performance, it can be concluded that:

- The proposed methods are given the best results compared with the real results of scheduling.
- The synchronous parallel hybridization of ABC in its three phases using the fitness function F is produced the best result.
- The synchronous parallel hybridization of ABC in its two phases (employed bees phase and scout bees phase) using the fitness function F is produced the equal results to the results of the synchronous parallel hybridization of ABC in its two phases (employed bees phase and scout bees phase) using the weighted sum method of the fitness function F.
- The synchronous parallel hybridization of ABC in its two phases using the weighted sum method of the fitness function F (employed bees phase and onlooker bees phase) is given 100% results equal to the results of the sequential hybridization of ABC with PSO using the weighted sum method of the fitness function F and equal to the results of the asynchronous parallel hybridization of ABC with PSO using the weighted sum method of the fitness function F.
- The sequential hybridization of ABC with PSO using the weighted sum method of the fitness function F is given the better results than the sequential hybridization of PSO with ABC using the fitness functions F1 and F2.
- The synchronous parallel hybridization ABC in its onlooker bees phase using the weighted sum method of the fitness function F is produced the equal results to the results of the sequential hybridization of ABC with PSO using two fitness functions F1 and F2.
- The synchronous parallel hybridization of ABC in its employed bees phase using the weighted sum method of the fitness function F is produced the equal results to the results of the sequential hybridization of ABC in its scout bees phase using the weighted sum method of the fitness function F.

The authors’ attention was concentrated not only on developing these three hybridization categories of the evolutionary methods ABC and PSO but also on tests of these hybrid methods in an automotive multi-objective flow shop and on their performance evaluation to make a performance comparison. The main limitation of the experimental that it is taken into account the fitness function F1/F2 only in the sequential hybridization of ABC and PSO.

### Table VI. The Synchronous Parallel Hybridization Methods HABCPSO2 / HABCPSO4 and the Asynchronous Parallel Hybridization Method ABC//PSO and the Sequential Hybridization Methods ABC(F1)+PSO(F2) / [PSO+ABC](F)

<table>
<thead>
<tr>
<th>Rank</th>
<th>Hybrid ABC and PSO</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Asynchronous parallel hybridization of ABC</td>
<td>ABC//PSO</td>
</tr>
<tr>
<td></td>
<td>and PSO</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Sequential hybridization of ABC and PSO</td>
<td>ABC(F1)+PSO(F2)</td>
</tr>
<tr>
<td>2</td>
<td>Synchronous parallel hybridization of ABC</td>
<td>HABCPSO2</td>
</tr>
<tr>
<td></td>
<td>and PSO</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Synchronous parallel hybridization of ABC</td>
<td>HABCPSO4</td>
</tr>
<tr>
<td></td>
<td>and PSO</td>
<td></td>
</tr>
</tbody>
</table>

The authors’ attention was concentrated not only on developing these three hybridization categories of the evolutionary methods ABC and PSO but also on tests of these hybrid methods in an automotive multi-objective flow shop and on their performance evaluation to make a performance comparison. The main limitation of the experimental that it is taken into account the fitness function F1/F2 only in the sequential hybridization of ABC and PSO.

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TABLE VII. THE RANKING OF ALL PROPOSED METHODS IN TERMS OF PERFORMANCE

<table>
<thead>
<tr>
<th>Ranking</th>
<th>Hybrid ABC and PSO</th>
<th>Employed bees phase</th>
<th>Onlooker bees phase</th>
<th>Scout bees phase</th>
<th>Hybridation number</th>
<th>Fitness function</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Synchronous parallel hybridization of ABC and PSO</td>
<td>HABCPSO3</td>
<td>PSO</td>
<td>PSO</td>
<td>3</td>
<td>F</td>
</tr>
<tr>
<td>2</td>
<td>Synchronous parallel hybridization of ABC and PSO</td>
<td>HABCPSO5</td>
<td>PSO</td>
<td>PSO</td>
<td>2</td>
<td>F</td>
</tr>
<tr>
<td>2</td>
<td>Synchronous parallel hybridization of ABC and PSO</td>
<td>HABCPSO6</td>
<td>PSO</td>
<td>PSO</td>
<td>2</td>
<td>F</td>
</tr>
<tr>
<td>3</td>
<td>Synchronous parallel hybridization of ABC and PSO</td>
<td>HABCPSO2</td>
<td>PSO</td>
<td>PSO</td>
<td>2</td>
<td>F</td>
</tr>
<tr>
<td>3</td>
<td>Sequential hybridization of ABC and PSO</td>
<td><a href="F">PSO+ABC</a></td>
<td>1</td>
<td>F</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Asynchronous parallel hybridization of ABC and PSO</td>
<td>ABC/PSO</td>
<td>1</td>
<td>F</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Sequential hybridization of ABC and PSO</td>
<td><a href="F">ABC+PSO</a></td>
<td>1</td>
<td>F</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Sequential hybridization of ABC and PSO</td>
<td>PSO(F1)+ABC(F2)</td>
<td>1</td>
<td>F and F2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Synchronous parallel hybridization of ABC and PSO</td>
<td>HABCPSO4</td>
<td>PSO</td>
<td>1</td>
<td>F and F2</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Sequential hybridization of ABC and PSO</td>
<td>ABC(F1)+PSO(F2)</td>
<td>1</td>
<td>F and F2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Synchronous parallel hybridization of ABC and PSO</td>
<td>HABCPSO1</td>
<td>PSO</td>
<td>1</td>
<td>F</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Synchronous parallel hybridization of ABC and PSO</td>
<td>HABCPSO7</td>
<td>PSO</td>
<td>1</td>
<td>F</td>
<td></td>
</tr>
</tbody>
</table>

IV. CONCLUSION

Powerful methods to solve the multi-objective flow shop scheduling problem are required, due to high level of its complexity.

An adequate hybridization of multiple algorithmic concepts is the key to accomplishing top performance in solving scheduling problems.

Based on the overall experimental results, it can be decided that the proposed methods were capable to solve multi-objective flow shop scheduling problem successfully, efficiently, and robustly in terms of solution quality.

The paper presents a pilot study for verifying how the multi hybridization and the hybridization categories influence the resolution of multi-objective flow shop scheduling problems.

The proposed methods have great potential for other applications such as multi-objective job shop scheduling problem resolution and multi-objective open-shop scheduling problem resolution.

As a future research, we intend to apply the ideas presented in this paper to other scheduling problems such as multi-objective job shop scheduling problem and multi-objective open-shop scheduling problem using other hybrid methods in three hybridization categories.

REFERENCES


