Effective Heuristics for the Bicriteria Scheduling Problem of Minimizing Total Tardiness and Total Flow Time with Zero Release Dates.

Saheed Akande
Department of Mechanical and Mechatronics Engineering,
Afe Babalola University, Ado-Ekiti. Nigeria.
sakande1@abuad.edu.ng

Ayodeji. E. Oluleye
Department of Industrial and Production Engineering
University of Ibadan, Ibadan. Nigeria.
ayodeji.oluleye@mail.ui.edu.ng

E.O. Oyetunji
Department of Mechanical Engineering
Lagos State University, Lagos. Nigeria
eoyetunji@yahoo.com

Abstract
We consider the bicriteria scheduling problem of minimizing the total tardiness and total flowtime on a single machine. This problem, which is known to be NP-hard, is important in practice, as the former criterion conveys the customer's position, and the latter reflects the manufacturer's perspective for optimal resources utilization. The simultaneous optimization approach was explored. Two heuristics to minimize the Linear Composite Objective Function (LCOF) of the two objectives were proposed. The utility of the proposed models was demonstrated through computational experiments and comparative analyses against existing solution methods and the Branch and Bound (BB) method. The results show that the proposed models yield efficient and near optimal schedules in most cases and perform better than the existing heuristics in the literature.

Keywords
Linear Composite Objective Function, Bi-criteria, Total Tardiness, Total Flowtime.

1. Introduction
A scheduling problem with only one criterion to be optimized is a single criterion problem. When more than one objective is to be optimized, it is called a multi-criteria problem. The simplest form of multi-criteria scheduling problems is the bi-criteria problem (M'Hallah, 2007; Oyetunji and Oluleye 2012). The advantages of implementing multi-criteria scheduling approaches over its single criteria constituents are enormous as they are preponderant in practice. For instance, exploring a schedule that minimizes only the total flowtime will ensure proper inventory management, reduction in production cost and profit maximization but offers no solution to late delivery of goods and services. Thus the firm may incur tardiness penalty or loses its goodwill. On the other hand, scheduling approaches for minimizing only the total tardiness will ensure prompt delivery of goods and services but with no consideration to profit variables. Therefore, combining the two criteria to form a bi-criteria problem will ensure the aggregation of the benefit of each component. In this regard, this paper considers the scheduling problem of minimizing the composite function of total flowtime and total tardiness.

2. Literature Review

Extensive literature review shows that several researchers have explored different bi-criteria scheduling problems. For instance, Tabucanon and Cenna, 1991 suggested a method to optimize mean flowtime and maximum tardiness by assigning weights to both criteria. They generated efficient schedules based on Van Wassenhove and Gelders, 1980 algorithm and used simulation approach to solve the problem. Erenay *et al*, 2010 considered the bi-criteria scheduling problem of minimising the number of tardy jobs and average flowtime on single machine. They proposed four heuristics; two of these heuristics were based on beam search methodology and other two based on metaheuristics approaches. From the analyses, it was concluded that the proposed beam search heuristics produced efficient schedules and performed better than the existing heuristics. A bi-criteria algorithm for simultaneous optimization of makespan (C_{max}) and number of tardy jobs (N_T) on single machine problem with sequence dependent set-up time was developed by Oladokun *et al.*, (2011). Two heuristics (called the HeuA and HeuB) to solve the problem of minimizing the total tardiness and total flowtime on single machine with zero release dates were proposed by Sen and Dillepan (1999). A Generalized Algorithm (GAlg) to solve the multi-criteria scheduling problem using the individual single objectives was proposed by Oyetunji and Oluleye (2012). Furthermore, Akande *et al.*, (2014), modelled some multi-criteria scheduling problems with more than two criteria to bi-criteria problems. The work was further validated through simulation using one of the multicriteria scheduling problem as a case study (Akande *et al.*, 2015). Therefore, only few solution methodologies were proposed for the problem considered in this paper. Sen and Dillepan claimed that the proposed heuristics were the first solution method to the problem and thus are not compared with any other model. Furthermore, the authors did not normalize the two objectives. Thus, there is no guarantee on the balance of the LCOF obtained. In this study, we present three new algorithms: two are constructive algorithms, based on the iterative search method, and the other one based on the GAlg. We compare these proposed heuristics with the HeuA and HeuB as well as the BB procedure. Due to the prohibitive execution time, the BB was applied to problem sizes not exceeding thirty jobs.

3. Problem Definition

This paper considers a single machine scheduling problem in which N jobs; $J_1, J_2, \dots J_n$ are to be scheduled with the objective of minimizing the total tardiness and total flowtime. In this environment, jobs have due dates (d_i) and deterministic processing times (P_i). We assume that pre-emption is not allowed and there exists no precedence constraints.

A job J_i is said to be tardy if it is completed after its due date (i.e. $C_i > d_i$).

The job tardiness $(T_i) = \max\{0, (C_i - d_i)\}$ (1)

The total tardiness (T_{tot}) : $\sum_{i=1}^{n} T_i = \sum_{i=1}^{n} max\,\{0, (C_i - d_i)$ (2)

The flowtime, (F_i) of job J_i is the time that job spends in the workshop. It is the interval between the release date (r_i) and the completion time (C_i) of the job.

$F_i = C_i - r_i$ (3)

The total flowtime (F_{tot}): $\sum_{i=1}^{n} F_i = \sum_{i=1}^{n} (C_i - r_i)$ (4)

The release date of all the jobs is zero,

$F_{tot} = \sum_{i=1}^{n} F_i = \sum_{i=1}^{n} C_i = F_i + F_2 + F_{i3} + - - F_n$ (5)

Using the simultaneous optimization approach, the problem is represented as:

$1 \,||\, (\sum_{i=1}^{n} T_i, \sum_{i=1}^{n} F_i)$

LCOF = $(\alpha \sum_{i=1}^{n} T_i + \beta \sum_{i=1}^{n} F_i)$ (6)

Where $\propto and\ \beta$ are the relative weights associated with the total tardiness and the total flowtime respectively.

$\alpha + \beta = 1$ (7)

In this work, a case of the total tardiness criterion being as important as the total flowtime criterion was considered.

$\alpha = \beta = 0.5$ (8)

LCOF = $0.5(\sum_{i=1}^{n} T_i + \sum_{i=1}^{n} F_i)$ (9)

4. Normalization

There are three approaches by which multi-criteria scheduling problems can be solved; the simultaneous, the hierarchical, and the pareto-optimal approaches. The simultaneous method was explored in this work. The approach gives a final schedule without further analysis unlike the pareto approach and also yields a balanced solution independent of the relative weight of each of the constituent criteria compared to the hierarchical method. However, the challenges of skewness (arising when the values of one criterion is a multiple of the other) and dimensional conflict (arising when the two criteria have different unit) limit the use of simultaneous optimization method. These problems were tackled through normalization proposition [Oluleye and Oyetunji 2009 : Akande *et al.*, 2015]. Thus, the value of each objective was normalised within the range of [0,1], thereby yielding dimensionless quantities (Oyetunji, 2012). It was showed that the normalized value of any criterion in a multicriteria problem can be expressed as:

$$X_N = \frac{X - X_{min}}{X_{max} - X_{min}} \quad (10)$$

where
X_N is the normalised value of the criterion,
X is the value of the criterion obtained from a given solution method,
X_{max} is the maximum value of the criterion, and
X_{min} is the minimum value of the criterion.
The minimum and the maximum possible values are called the extreme values. Finding the extreme values is a necessary condition to obtain the normalized value of a criteria. Table 1 shows the equations used to determine the extreme values of the two objectives (Akande *et al.*, 2015)

Table 1. The extreme values of the total flowtime and total tardiness

Objective function	minimum value	maximum value
The total flowtime	$\sum_{1}^{n} P_i$	$n\left\{\sum_{i=1}^{n-1} P_i\right\} + \sum_{i=1}^{n} P_i$ $For\ k = 2{:}\,n-1$
The total tardiness	0	$C_{tot}^{max} - \sum_{i=1}^{n} (d_i)$

Therefore, once the normalized value of the two criteria are determined, the normalized composite objective function of the multi-criteria problem is given by

$$NTLCOF = 0.5\,(NT_X + NF_Y) \quad (11)$$

where:
$NTLCOF$ is the normalized total composite function
NT_X is the normalized value of total tardiness
NF_Y is the normalized value of total flowtime
The value of NTLCOF was used to assess the performances of the solution methods to the problem.

5. Materials and methods

5.1 Solution methods from the literature

i. HeuA: The jobs are arranged in EDD. If there is a string of consecutive tardy jobs at the end of the sequence, the tardy jobs are rearranged in SPT.
ii. HeuB: The jobs are arranged in non-decreasing order of $p_i - d_i$. If there is a string of consecutive tardy jobs at the end of the sequence, the tardy jobs are rearranged in SPT.

5.2 The Generalized Algorithm (GAlg)

The algorithm required, as input, the schedules from the individual criterion that makes the multi-criteria problem. In this work, the flowtime was minimized using Shortest Processing Time (SPT) (Smith, 1956) while the total tardiness was minimized using the Modified Due Date (MDD) rule (Baker and Betrand, 1982).

5.3 The Branch and Bound (BB) method

The BB is a solution method that yields optimal results in terms of effectiveness. However, the method requires a prohibitively high computation time for large-sized problems. This limits the applications of the method for real life problems. In this work, the frontier search method was explored to branch while the GAlg was used to bound the branching tree. Let *s* denote a partial sequence of jobs from among the *n* jobs originally in the problem, let j(s) denote the partial sequence in which *s* is immediately preceded by job *j*. Associated with j(s) is a value, V_s which is the contribution of assigned jobs in each level to the total LCOF. The value of V_s was calculated for all the nodes at each level and compared to the lower bound obtained from the GAlg. Then, the node(s) with V_s higher than the lower bound value obtained from the GAlg are discarded while other nodes are further explored. The process continues until all the jobs are scheduled.

5.4. Proposed solution methods

i. **HEU 1**: Mathematical analysis of the two criteria shows that any solution method that optimizes either of the criteria must also optimize the completion time. Analysis of the MDD algorithm shows that the rule favours the Early Due Date (EDD) rule at the beginning of a schedule while towards the tail end, MDD algorithm produces the same schedule as SPT rule. In this regard, if the two individual optimal solutions are equivalent, either of them will produce a very good solutions for the bi-criteria problem. Furthermore, if the two individual solutions differ, then either the schedule produced by one of the algorithms or a very close neighbour will yield a good solution.

The statement of the algorithm are as follows;
Initialization:
JobSet A = [J_1, J_2, J_3, …….J_n], set of given jobs, JobSet B = [0], set of schedules job
JobSet C = [J_1', J_2', J_3', . . . J_n'], set of unscheduled jobs, $J_j' = J_j$
STEP 1: Form JobSet D by arrange the jobs in order of increasing processing time.
STEP2: Form JobSet E by exploring modified due date algorithm.
STEP 3: Compute the LCOF function; LCOF1 and LCOF2 for both JobSet D and JobSet E respectively.
STEP 4: Set JobSet E as the required schedule (JobSet B) if LCOF2 is less than or equal to LCOF1, otherwise set JobSet D as the required schedule.
STEP 5: Compute the objective function of the required schedule.
STEP 6: Stop.

ii. **HEU II:** This algorithm is based on the two parameters upon which the two criteria depend. These are the processing time and the due date.
Initialization:
JobSet A = [J_1, J_2, J_3, …….J_n], set of given jobs, JobSet B = [0], set of schedules job
JobSet C = [J_1', J_2', J_3', …….J_n'], set of unscheduled jobs, $J_j' = J_j$
STEP 1: Arrange the JobSet A in order of increasing processing time.
STEP 2: Break the tie in STEP 1 1 by using the modified due date rule.
STEP 3: Compute the objective function of the schedule
STEP 4: Stop

6. Data Analysis

A total of 16 problem sizes ranging from 5 to 1000 jobs and 50 problem instances under each problem size were randomly generated. The processing times were randomly generated from 1-10. The due dates were generated using the equation $K*p$ with k ranging from1-4 inclusive as in Gursel *et al.,* (2012). Coding was carried out in MATLAB 7.10 using a personal computer of 1.70GHz processor and 4.0GB RAM. The program computes the normalized LCOF value for each problem instance, the total normalized LCOF values for 50 problem instances, and the mean of normalized LCOF values. The program also computes the mean execution time for 50 problem instances. The results obtained were subjected to different comparative analyses. The results are presented in section 7.

7. Results and Discussions

The results are based on the effectiveness (closeness of the objective value to the optimal) and the efficiency (the execution time to solve each instance of the problem).

7.1 Results based on effectiveness:

The mean values of the total LCOF obtained from the four solution methods and the considered problem sizes are shown in Table 2.

Table 2. Mean value of the normalized total LCOF

S/N	Problem sizes	GAlg	HEUA	HEUB	HEU I	HEU II	BB
1	5x1	0.2975	0.2900	0.5689	0.2823	0.3130	0.2823
2	10x1	0.3293	0.3451	0.5568	0.3281	0.3304	0.3281
3	15x1	0.3353	0.357	0.5684	0.3345	0.3355	0.3345
4	20x1	0.3440	0.3669	0.571	0.3437	0.3441	0.3436
5	25x1	0.3413	0.3648	0.5765	0.3411	0.3413	0.341
6	30x1	0.3439	0.3675	0.5777	0.3438	0.3439	0.3436
7	40x1	0.3480	0.3718	0.5776	0.3478	0.3479	
8	60x1	0.3476	0.3708	0.5873	0.3476	0.3477	
9	80 x1	0.3478	0.3715	0.5891	0.3478	0.3479	
10	100 x1	0.3489	0.3740	0.5848	0.3489	0.3489	
11	150 x1	0.3509	0.3746	0.5892	0.3507	0.3508	
12	200 x1	0.3491	0.3738	0.5891	0.3491	0.3491	
13	300 x1	0.3511	0.3751	0.59	0.3511	0.3511	
14	400 x1	0.3528	0.3773	0.588	0.3501	0.3503	
15	500 x1	0.3519	0.3761	0.5897	0.3519	0.3519	
16	1000 x1	0.3523	0.3766	0.5987	0.3523	0.3523	

The results obtained showed that the solution methods can be ranked in the order: HEU I, GAlg, HEU II, HEUA, HEUB. Furthermore, in order to measure the performances of the methods, the following comparative tests were carried out.

i. **The t-test:** To ascertain whether the differences observed were significant, t-tests for paired two-samples for means were carried out using the Spreadsheet 2013 data analysis ($p < 0.05$). Tables 3 and 4 show the results of the t-test for the problem ranges; $5 \leq n \leq 30$ and $30 \leq n \leq 1000$ respectively.

Table 3. T-test for $5 \leq n \leq 30$ problems ranges

Solution method	GAlg	HEU 1	HEU II	HEUA	HEUB	BB
GAlg	----	>0.05	>0.05	<0.05*	<0.05*	>0.05
HEU 1	>0.05	------	>0.05	<0.05*	<0.05*	>0.05
HEU II	>0.05	>0.05	-----	<0.05*	<0.05*	>0.05
HEUA	<0.05*	<0.05*	>0.05	--------	>0.05	<0.05*
HEUB	<0.05*	<0.05*	<0.05*	>0.05	--------	<0.05*
BB	>0.05	>0.05	>0.05	<0.05*	<0.05*	---------

Table 4. T-test for $30 \leq n \leq 1000$ problems ranges

Solution method	GAlg	HEU 1	HEU II	HEUA	HEUB
GAlg	----	>0.05	>0.05	<0.05*	<0.05*
HEU I	>0.05	------	>0.05	<0.05*	<0.05*
HEU II	>0.05	>0.05	-----	<0.05*	<0.05*
HEUA	<0.05*	<0.05*	<0.05*	--------	>0.05
HEUB	<0.05*	<0.05*	<0.05*	>0.05	--------

*Note: * indicates significant result; Sample size = 50; ---- indicates not necessary*

The t-tests results show that the differences in the performances of all the solution methods are not significant with the exception of HEUA and HEUB. Other solution methods; HEU I, GAlg, and HEU II are significantly better ($p < 0.05$).

ii. **The approximation ratio (AR) test:** The A.R of a heuristic is the ratio of the value of the objective function obtained from the heuristic to the benchmark value ($\boldsymbol{BM_{value}}$). The $\boldsymbol{BM_{value}}$ is either the optimal value from the BB or the standard value from the best heuristic. The ratio gives the indication of the closeness or otherwise of the objective function of the proposed algorithm against the standard. A lower A.R value indicates better performance for minimization problems. The A.R of a HEU I is given by:

$$A.R_{HEU\ 1} = \frac{HEU\ I_{Value}}{BM_{value}} \quad (12)$$

where:
$HEU\ I_{Value}$ is the value of objective function using the HEU I
BM_{value} is the benchmark value.
The BB solution results were used as the benchmark in the problem range $5 \le n \le 30$ while the HEU 1 was used in the problem ranges; $40 \le n \le 1000$.

Figure 1 shows the plots of approximation ratio of the solution methods in the problem range $5 \le n \le 30$. The plots confirmed the established ranking order as the HEUB and HEUA are far away from the optimal plot compared to the other solution methods.

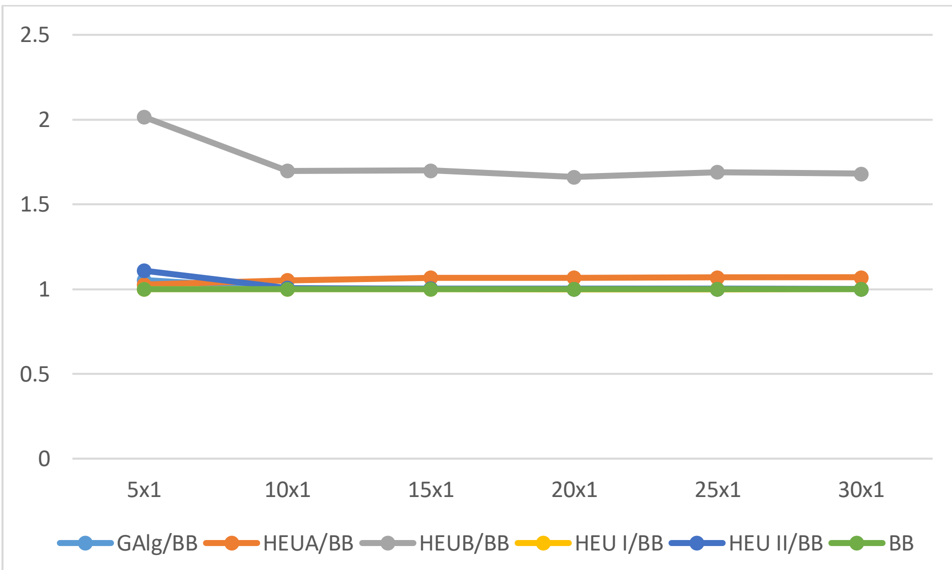

Figure 1. A plot of approximation ratio of solution methods for $5 \le n \le 30$

Furthermore, Table 5 shows the overall means of approximation ratio of all the solution methods for the problem ranges; $5 \le n \le 30$. The table implies that the heuristics HEU 1, HEU II, GAlg, HEUA, HEUB are 1.0002, 1.02, 1.01, 1.06 and 1.74 times the optimal value respectively.

Table 5. The overall means of approximation ratio for ranges; $5 \le n \le 30$.

Solution methods	Overall means of approximation ratio
HEU 1	1.0002
HEU II	1.02
GAlg	1.01
HEUA	1.06
HEUB	1.74

Similarly, figure 2 shows the approximation ratio plots for the solution methods in the problem range; $40 \le n \le 1000$. The plots show that other solution methods aligned while the HEUA and the HEUB show a visible difference.

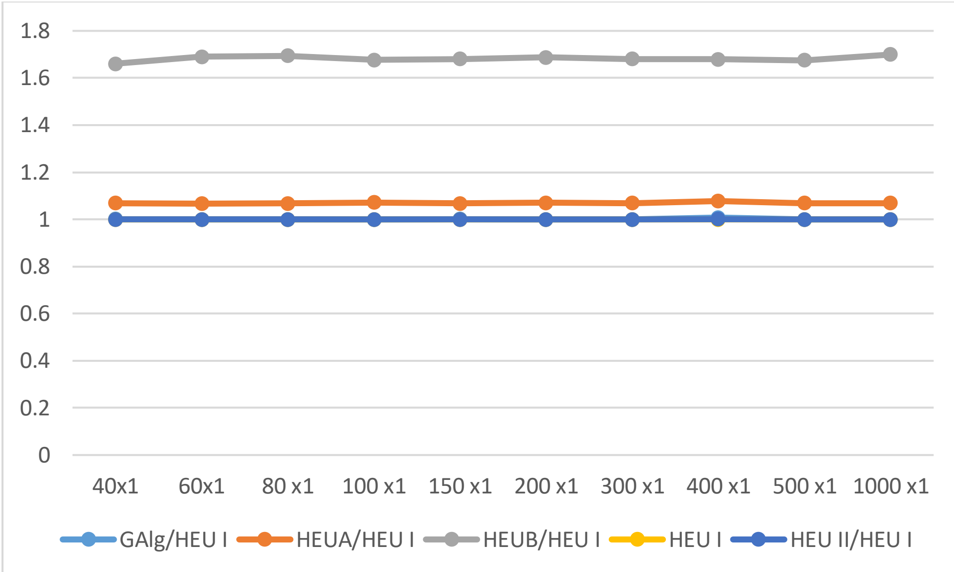

Figure 2. A plot of approximation ratio by problem sizes for 40≤n ≤ 1000.

Furthermore, Table 6 shows the overall means of approximation ratio of the solution methods for the problem ranges; 40≤n ≤ 1000.

Table 6. The overall means of approximation ratio for 40 ≤ n ≤ 1000

Solution methods	Overall means of approximation ratio
HEU II	1.02
GAlg	1.0009
HEUA	1.0002
HEUB	1.68

7.2 Results based on the efficiency

The mean of execution time to complete each problem sizes was computed. Table 8 shows the mean of the total execution time by solution methods and problem sizes.

Table 8: Mean of the total execution time by solution methods and problem sizes

Sizes	GAlg	HEUA	HEUB	HEU 1	HEU II	BB
5 x 1	0.0036	0.00065	0.00081	0.0016	0.0027	2486.25
10 x 1	0.0039	0.00076	0.00085	0.0019	0.0035	3472.12
15x1	0.0041	0.00087	0.0009	0.0021	0.0045	5243.23
20 x 1	0.0045	0.00092	0.00094	0.0023	0.0058	7453.54
25x1	0.0056	0.00098	0.00097	0.0027	0.0064	9145.62
30x1	0.0068	0.001	0.0011	0.003	0.0076	13794.1
40x1	0.009	0.0015	0.0012	0.0033	0.0081	
60x1	0.0073	0.0015	0.0018	0.009	0.0088	
80 x1	0.0088	0.002	0.0019	0.061	0.0114	
100 x1	0.0108	0.0027	0.0025	0.074	0.0155	
150 x1	0.0155	0.003	0.0037	0.017	0.023	
200 x1	0.0197	0.0041	0.0041	0.016	0.0284	
300 x1	0.0283	0.0064	0.0055	0.0226	0.0382	
400 x1	0.0374	0.0081	0.0081	0.0301	0.0517	
500 x1	0.047	0.01	0.01	0.0395	0.0644	
1000 x1	0.1136	0.0219	0.022	0.0955	0.1274	

The results based on the execution time show that the HEUA has the lowest execution time while the BB has the highest execution time. However, to ascertain whether the differences observed between the execution time of all the heuristics were significant, statistical t-test of paired two-samples for means were carried out using Spreadsheet 2013 data analysis. Table 9 shows the result of the t-test.

Table 9: t-test for the execution time

Solution method	GAlg	HEU 1	HEU II	HEUA	HEUB
GAlg	----	>0.05	>0.05	>0.05	>0.05
HEU 1	>0.05	------	>0.05	>0.05	>0.05
HEU II	>0.05	>0.05	-----	>0.05	>0.05
HEUA	>0.05	>0.05	>0.05	>0.05	>0.05
HEUB	>0.05	>0.05	>0.05	>0.05	>0.05

The results of t-test show that the execution time of all the heuristics are not significantly different from each other. Essentially, they are polynomial time algorithms (except the BB which require a prohibitive execution time). Moreover, in order to rank the solution methods in respect of efficiency, approximation ratio test was also carried out. HeuA was used as the standard because it has the lowest execution time. Figure 3 shows the plot of the approximation ratio

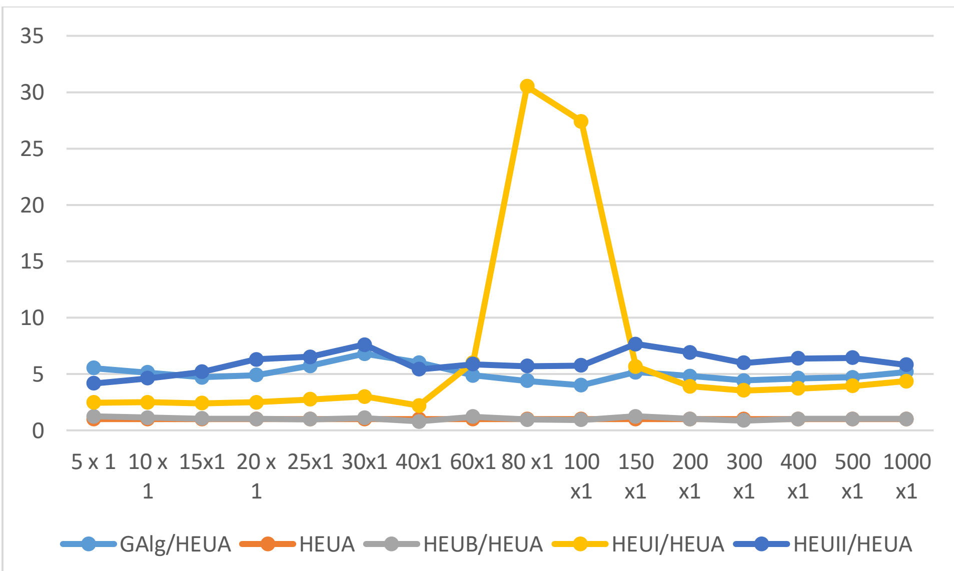

Figure 3: The plots of approximation ratio for all the implemented solution method

Table 10 shows the overall means of approximation ratio of the solution methods. The results show that HEUA is faster than HEU 1, HEU II, GAlg and HEUB by 6.02, 6.68, 5.06 and 1.08 times respectively.

Table 10: The overall means of approximation ratio for $5 \leq n \leq 1000$

Solution methods	Overall means of approximation ratio
HEU II	6.02
HEU 1	6.68
GAlg	5.06
HEUB	1.08

8. Conclusion and recommendation

This paper proposed two heuristics for minimizing the LCOF of total tardiness and total flowtime on single machine with zero release dates. Result of simulation shows that for the considered problem sizes; $5 \leq n \leq 1000$, the implemented GAlg and the two proposed heuristics performed significantly better than the HeuA and HeuB from the literature. The implemented GAlg and the two proposed heuristics produced results that are not significantly different from each other. Also in terms of efficiency, though HeuA and HeuB have lower execution time, their execution time are not statistically different from the proposed effective solution methods.

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Biographies

Akande Saheed is a Lecturer in the Afe Babalola University, Ado-Ekiti, Department of Mechanical and Mechatronics Engineering. He earned B.Sc. in Metallurgical and Materials Engineering from Obafemi Awolowo University, Ile-ife, Nigeria. Masters and Ph.D in Industrial and Production Engineering, University of Ibadan. Nigeria. He has published some journal and conference papers. His research interests include scheduling, manufacturing, simulation, optimization. He is a Registered Engineer (COREN) and a Member of the Nigeria Society of Engineers (NSE), Nigerian Institute of Industrial Engineering (NIIE).

Ayodeji E. Oluleye is a Professor in the University of Ibadan's Department of Industrial and Production Engineering. He earned B.Sc (Hons.) in Agricultural Engineering from University of Ibadan, Nigeria. Master in Agricultural Machinery Engineering, from Cranfield Institute of Technology, England and Ph.D in Industrial Engineering, University of Ibadan. His research interest includes production scheduling/operations management (optimization), and algorithm design, engineering economics amongst, others. He has published extensively in prestigious journals. He is a Registered Engineer (COREN) and a Member of the Nigeria Society of Engineers (NSE), and a Fellow of the Nigerian Institute of Industrial Engineering (NIIE).

E.O. Oyetunji is currently a Professor of Industrial and Production Engineering in the Department of Mechanical Engineering, Faculty of Engineering, Lagos State University, Epe Campus, Lagos, Nigeria. He graduated with a BSc (Hons) in Electrical Engineering from the University of Ilorin, Ilorin, Nigeria. He has an MSc and PhD in Industrial Engineering from the University of Ibadan, Ibadan, Nigeria. He has attended numerous national and international conferences. His research interest includes production scheduling/operations management (optimization), and algorithm design amongst others. He has published extensively in prestigious local and international journals. He is a Registered Engineer (COREN) and a Member of the following professional bodies: Nigeria Society of Engineers (NSE), Nigeria Institute of Industrial Engineering (NIIE).