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Optimization of Energy Resource Management for Assembly Line Balancing Using Adaptive Current Search

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ABSTRACT

This paper aimed to present the optimization of energy resource management in a car factory by the adaptive current search (ACS)—one of the most efficient metaheuristic optimization search techniques. Assembly lines of a specific car factory considered as a case study are balanced by the ACS to optimize their energy resource management. The workload variance of the line is performed as the objective function to be minimized in order to increase the productivity. In this work, the ACS is used to address the number of tasks assigned for each workstation, while the sequence of tasks is assigned by factory. Three real-world assembly line balancing (ALB) problems from a specific car factory are tested. Results obtained by the ACS are compared with those obtained by the genetic algorithm (GA), tabu search (TS) and current search (CS). As results, the ACS outperforms other algorithms. By using the ACS, the productivity can be increased and the energy consumption of the lines can be decreased significantly.

KEYWORDS

Adaptive Current Search; Assembly Line Balancing; Energy Resource Management; Metaheuristic Optimization

1. Introduction

Metaheuristic optimization is one of the most important issues in computer science and operation research. According to the energy resource optimization context, energy resource management is an alternative to increase the productivity or decrease the energy consumption. Especially in car assembly industries, total energy of such industries can be divided into two parts, *i.e.* main energy used for assembling products and supporting energy used for illumination, ventilation and so on. Minimized workload variance of the assembly line can increase productivity and also increase energy efficiency. Energy resource management can be considered as a class of non-polynomial time hard (NP-hard) combinatorial optimization problem [1,2]. So the problem usually possesses nonlinear and unsymmetrical terms as well as multiple local solutions. These cause the problem complex and difficult to solve by an exact method within a reasonable amount of time. In addition, inefficient algorithms are easily trapped due to its local solutions. To solve the problem, metaheuristic optimization methods are alternatives [3-5]. Over five decades, many metaheuristics such as genetic algorithm (GA), tabu search (TS), particle swarm optimization (PSO) and harmony search (HS) have been developed for combinatorial, continuous and multiobjective optimization problems [5,6]. Metaheuristics has been widely applied to various real-world engineering problems [7,8]. Some metaheuristics such as GA, TS, PSO and HS have been accepted and applied to some energy saving and management applications [9-12].

By literatures, several methods have been launched to solve the assembly line balancing (ALB) problems, for example, heuristic approaches [13,14], metaheuristics such as GA [15] and TS [16,17], and hybrid methods [18,19]. Although GA and TS could provide satisfactory results, they may be trapped by some local optima and spent amount of search time. One of the latest metahueristics is the current search (CS) [20]. The CS has been successfully applied to control engineering [21] and signal processing [22]. However, local entrapments in CS may be occurred. In order to improve its effectiveness, the CS needs to be modified. The modified version of the CS named adaptive current search (ACS) has been proposed [23]. The ACS shows the superior results to the conventional CS and other metaheuristic algorithms.

This paper proposes the application of the ACS to optimize energy resource management in a car factory. Three real-world assembly line balancing (ALB) problems from a specific car factory are conducted. The workload variance of such lines is minimized in order to increase the productivity and decrease the energy consumption. After an introduction in Section 1, the problem formulation of energy resource management of ALB problems is explained in Section 2. The ACS algorithms are briefly described in Section 3. Results of solving ALB problems by the ACS compared with GA, TS and CS are provided in Section 4, while discussions and conclusions are given in Section 5 and Section 6, respectively.

2. Problem Formulation

The problem formulation of energy resource management of ALB problems of a car factory in sense of energy resource management is presented in this Section. The ALB problem is considered as one of the classical industrial engineering problems [24]. An assembly line is a sequence of workstations connected together by a material handling system. It is used to assemble components or tasks into a final product. The fundamental of the line balancing problems is to assign the tasks to an ordered sequence of workstations in order to minimize the workload variance of the line, whereas satisfying two particular constraints. The first constraint is that the total processing time assigned to each workstation should be less than or equal to the cycle time. The second is that the task assignments should follow the sequential processing order of the tasks or the precedence constraints.

The ALB can be considered as the class of combinatorial optimization problems known as NP-hard [13,25]. Traditionally, the assembly line will be represented by the precedent diagram. **Figure 1** shows the precedent diagram of a simple assembly line consisting of 29 tasks, where node weight stands for the task time in time units.

In this work, the single-model ALB problem is considered. Balancing of the lines can be measured by the workload variance [14,25]. Therefore, the goals of balancing lines are to minimize the workload variance. Analytical formulations for the ALB problems are stated in (1) - (4), where m is the number of workstations, W is the total processing time, c is the cycle time, T_i is the processing time of the i^{th} workstation, T_{id} is the idle time, w_v is the workload variance and E is the line efficiency.

$$m = W/c \tag{1}$$

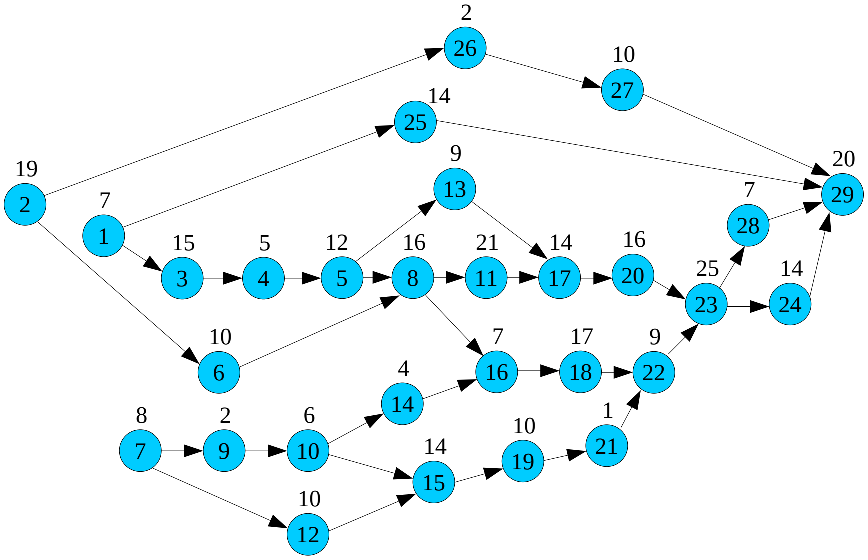


Figure 1. **Precedent diagram of simple assembly line.**

$$T_{id} = \sum_{i=1}^{m} (c - T_i) \tag{2}$$

$$w_v = \frac{1}{m} \sum_{i=1}^{m} \left[T_i - (W/m)\right]^2 \tag{3}$$

$$E = \sum_{i=1}^{m} T_i / (m \times c) \tag{4}$$

The ALB problem can be considered as the constrained optimization problem. The workload variance (w_v) is performed as the objective function (J) stated in (5). J will be minimized according to the precedence constraints expressed in (6). Moreover, the constraint in (6) also indicates that the processing time T_i of the i^{th} workstation must equal or less than the cycle time (c).

$$J = w_v = \frac{1}{m} \sum_{i=1}^{m} \left[T_i - (W/m)\right]^2 \tag{5}$$

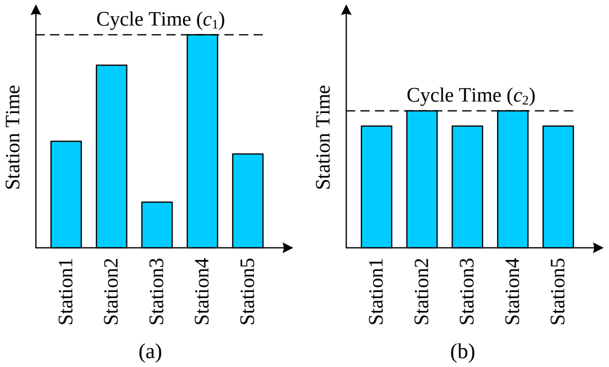
$$\begin{aligned} &\text{minimize} && J \\ &\text{subject to} && T_i \le c, \\ & && \text{precedent constrains} \end{aligned} \tag{6}$$

Once w_v is reduced, E is then increased. Working time to complete the product can be also reduced. In sense of energy resource management, reduced workload variance can increase productivity and decrease total energy consumption. This approach can be represented by **Figure 2**. Assume that the total energy of the line consists of main energy used for assembling products and supporting energy used for illumination and ventilation systems. Total energy (Z_{total}) is stated in (7), where Z_{main} is the main energy used for assembly and Z_{support} is the supporting energy used for illumination and ventilation, respectively.

$$Z_{\text{total}} = Z_{\text{main}} + Z_{\text{support}} \tag{7}$$

Referring to **Figure 2**, a simple assembly line consists of 5 workstations. Time for finishing each product of unbalanced line in **Figure 2(a)** is equal to cycle time (c_1), while that for finishing each product of balanced line in **Figure 2(b)** is equal to cycle time (c_2). Once $c_2 < c_1$, this means that time for finishing each product of balanced line is less than unbalanced line does. Total energy per product ($Z_{\text{total/product}}$) and supporting energy per product ($Z_{\text{support/product}}$) can be calculated by (8) and (9), where N_{item} is numbers of products produced within a certain period. It was found that, although the main energy used for assembling each product is a same value between unbalanced and balanced lines, total energy per product ($Z_{\text{total/product}}$) and supporting energy per product ($Z_{\text{support/product}}$) can be decreased when cycle time is reduced. By this approach, productivity can be increased and also total energy consumption can be decreased.

$$Z_{\text{total/product}} = \frac{Z_{\text{total}}}{N_{\text{item}}} = \frac{Z_{\text{main}} + Z_{\text{support}}}{N_{\text{item}}} \tag{8}$$



(a) (b)

Figure 2. Assembly line consisting of 5 workstations: (a) unbalanced line, (b) balanced line.

$$Z_{\text{support/product}} = \frac{Z_{\text{support}}}{N_{\text{item}}} \tag{9}$$

3. ACS Algorithm

In 2012, the current search (CS) was developed based on the principle of current divider in electric circuit theory [20-22]. The CS possesses both exploration and exploitation properties according to the metaheuristic optimization context. The advantages of the CS are that it can find any local solution in each search direction efficiently. It can perform unlimited search directions defined by users. However, the disadvantages of the CS are that its search process may be trapped or locked by any local solution. In addition, the search time consumed by the CS is depended on the numbers of search directions.

The adaptive current search (ACS), the modified version of the CS, is proposed in 2013 [23]. It provides the memory list (ML) and the adaptive radius (AR) mechanism inserting into the CS algorithms. The ML is used to escape from local entrapment caused by any local solution, while the AR is conducted to speed up the search process. The proposed ML consists of three levels: low, medium and high. The low-level ML is used to store the ranked initial solutions at the beginning of search process, the medium-level ML is conducted to store the solution found along each search direction, and the high-level ML is used to store all local solutions found at the end of each search direction. Performance evaluation of the ACS was performed against benchmark unconstrained and constrained optimization problems [23]. Compared with genetic algorithm (GA), tabu search (TS) and current search (CS), it was found that the ACS shows the superior results to the conventional CS and other algorithms. Some movements of the ACS search process over the search space can be depicted in Figure 3. The ACS algorithm is described as follows:

Step 1 Initialize the search space Ω, iteration counter $k = j = 1$, maximum allowance of solution cycling $j_{\mathbf{max}}$, number of initial solutions N, number of neighborhood members n, search radius R, and low-level ML $\Psi = \varnothing$, medium-level ML $\Gamma = \varnothing$, and high-level ML $\Xi = \varnothing$.

Step 2 Uniformly random initial solution X_i, $i = 1,\cdots,N$ within Ω.

Step 3 Evaluate the objective function $f(X_i)$ for $\forall X$. Rank X_i that gives $f(X_1) <\cdots< f(X_N)$, then store ranked X_i into the low-level ML Ψ.

Step 4 Let $x_0 = x_k$ as selected initial solution.

Step 5 Uniformly random neighborhood x_i, $i = 1,\cdots,n$ around x_0 within radius R.

Step 6 Evaluate the objective function $f(x_i)$ for $\forall x$. A solution giving the minimum objective function is set as x^*.

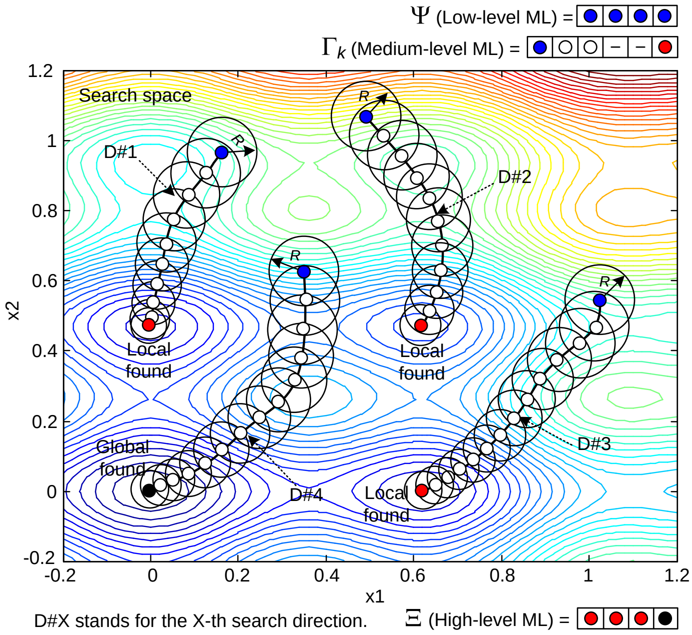


Figure 3. Some movements of ACS algorithm.

Step 7 If $f\left(x^{*}\right)<f\left(x_0\right)$, keep x_0 into medium-level ML Γ_k and set $x_0 = x^*$, set $j = 1$ and return to Step 5. Otherwise keep x^* into medium-level ML Γ_k and update $j = j + 1$.

Step 8 If the search process moves close to the local solution, activate the AR mechanism by adjusting $R = \rho R$, $0 < \rho < 1$.

Step 9 If $j < j_{\mathbf{max}}$, return to Step 5. Otherwise keep x_0 into high-level ML Ξ and update $k = k + 1$.

Step 10 Terminate the search process when the termination criteria (TC) are met. The optimum solution found is x_0. Otherwise return to Step 4.

4. Experimental Results

This Section presents the application of the ACS to optimize energy resource management of assembly line balancing (ALB) problems in a car factory. Sammitr Motors Manufacturing Public Co., Ltd. [26], a car factory located in Samut Sakhon, Thailand, is considered as a case study of this work. It produces car and truck body parts, moulds and fixtures for auto makers such as HINO, ISUZU, MITSUBISHI and NISSAN. Many kinds of car and truck body parts under "Sammitr" trademark are assembled from this factory. For a truck, it comprises of several parts, such as turning disk, dragging arm, frame, rear cap, side cap and so forth. In this factory, each part belongs itself assembly line. For this work, three ALB problems of that car factory, *i.e.* turning disk, dragging arm and frame assembly lines, are selected. Details of the selected ALB problems are described as follows.

- For the first ALB problem, turning disk assembly line consists of 63 tasks with total working time of 459.63 min. Details of turning disk assembly line are provided in Appendix, for example. Among those tasks, there are 24 tasks for welding (278.20 min.), 9 tasks for grinding and eroding (57.80 min.) and 11 tasks for moving (26.55 min.). Data from factory reveal that there are 5 workstations with the cycle time of 152.33 min. This means that time for finishing each product of this line is equal to 152.33 min.
- For the second ALB problem, dragging arm assembly line consists of 70 tasks with total working time of 307.41 min. Among them, there are 29 tasks for welding (184.67 min.), 7 tasks for grinding and eroding (36.28 min.) and 6 tasks for moving (18.00 min.). Data from factory show that there are 6 workstations with the cycle time of 123.02 min. Time for finishing each product of this line is equal to 123.02 min.
- For the third ALB problem, frame assembly line consists of 75 tasks with total working time of 1,334.27 min. Among them, there are 34 tasks for welding (853.95 min.), 4 tasks for grinding and eroding (55.71 min.) and 9 tasks for moving (165.28 min.). Data from factory indicate that there are 5 workstations with the cycle time of 651.94 min. This means that time for finishing each product of this line is equal to 651.94 min.

All three lines are run 440 min. per day, 25 days per month and 12 months per year. Power used for completing the product consists of one welding machine of 13 kW (α_1 = 13,000 W × 1), one grinding and eroding motor of 1 Hp (α_2 = 746 W × 1) and one crane motor of 2 Hp (α_3 = 1,492 W × 1). Power used for illumination system comes from 18 halogen lamps of 400 W (β_1 = 400 W × 18) and 84 fluorescent lamps with their ballasts of 36 W + 10 W (β_2 = 46 W × 84). Power used for ventilation system comes from 12 motors of 3/4Hp (γ = 559.50 W × 12). Therefore, the main energy used for assembly (Z_{main}) and the supporting energy used for illumination and ventilation ($Z_{support}$) of these lines can be yearly calculated in kilowatt-hour (kWh) unit by (10) and (11), where T_1 is time for welding, T_2 is time for grinding and eroding, and T_3 is time for moving. In this work, power for cutting, blowing, drilling and broaching are neglected.

$$Z_{\text{main}} = \frac{N_{\text{item}} \times \sum_{i=1}^{3}\left(\alpha_i \times T_i\right)}{60 \times 1,000} \tag{10}$$

$$Z_{\text{support}} = \underbrace{\left(\frac{(\beta_1+\beta_2)\times 12\times 25\times 440)}{60\times 1,000}\right)}_{\text{illumination}} + \underbrace{\left(\frac{\gamma\times 12\times 25\times 440)}{60\times 1,000}\right)}_{\text{ventilation}} \tag{11}$$

Data of all three ALB problems from factory are summarized in **Table 1**. In this work, the ACS is conducted to solve the ALB problems. The ACS is used to address the number of tasks assigned for each workstation, while the sequence of tasks was assigned by factory. The workload variance (w_v) performed as the objective function (J) stated in (5) will be minimized according to the precedence constraints expressed in (6).

In this paper, algorithms of GA and TS are omitted. Readers may refer to [27,28] for GA and [29,30] for TS, respectively. For all three ALB problems, the parameter settings for the GA follow MATLAB-GA Toolbox [28]

Table 1. Details of selected ALB problems.

Data	ALB problems		
	Tuning Disk	Dragging Arm	Frame
n (tasks)	63	70	75
W (min.)	459.63	307.41	1,334.27
c (min.)	152.33	123.02	651.94
m (stations)	5	6	5
α_1 (W)	13,000 W × 1	13,000 W × 1	13,000 W × 1
α_2 (W)	746 W × 1	746 W × 1	746 W × 1
α_3 (W)	1,492 W × 1	1,492 W × 1	1,492 W × 1
β_1 (W)	400 W × 18	400 W × 18	400 W × 18
β_2 (W)	46 W × 84	46 W × 84	46 W × 84
γ (W)	559.50 W × 12	559.50 W × 12	559.50 W × 12
T_1 (min.)	278.20	184.67	853.95
T_2 (min.)	57.80	36.28	55.71
T_3 (min.)	26.55	18.00	165.28

and for the TS follow [30]. The common search parameters of the CS and ACS are: n (number of neighborhood members) = 1,000, R (search radius) = 20% of search space and $I_{\max}$ (number of iterations) = 1,000. N (number of search directions) = 10 is required to terminate the search. For the ACS, R-adjustment (search radius adjustment of AR mechanism) is set as $I_{\max} = 500 \rightarrow R = 10\%$ of search space and $I_{\max} = 750 \rightarrow R = 5\%$ of search space.

The TS, CS and ACS algorithms were coded by MATLAB, while GA was conducted from MATLAB-GA Toolbox. All algorithms were run on Intel Core2 Duo 2.0 GHz 3 Gbytes DDR-RAM computer. **Table 2** provides the boundaries of number of tasks for each workstation set for the corresponding search spaces. For all algorithms, 50 trials were run to obtain the best solution. Results obtained are summarized in **Table 3**, while convergent rates are plotted in **Figure 4**-**Figure 6**.

5. Discussions

As results of the first ALB problem in **Table 3**, turning disk assembly line arranged by factory and optimized by GA, TS, CS and ACS can be plotted in **Figure 7**-**Figure 11** and **Table 4**-**Table 8**, respectively. The ACS provides superior results to other algorithms and certainly a factory. The workload variance (w_v) obtained by the ACS is less than that obtained by GA, TS and CS. Once w_v is reduced, the line efficiency (E) will be increased. It can be observed that E in **Table 3** optimized by the ACS is the highest value.

By those results, percent of decreased total energy per produce (*PDTE*) and percent of decreased supporting energy per produce (*PDSE*) can be calculated by (12) and (13), where $Z_{\text{total/product,old}}$ is total energy per produce of factory, $Z_{\text{total/product,new}}$ is total energy per produce obtained by GA, TS, CS or ACS, $Z_{\text{support/product,old}}$ is supporting energy per produce of factory, and $Z_{\text{support/product,new}}$ is supporting energy per produce obtained by GA, TS, CS or ACS. Results are summarized in **Table 9**.

$$PDTE = 100 \times \left(\frac{Z_{\text{total/product,old}} - Z_{\text{total/product,new}}}{Z_{\text{total/product,old}}} \right) \tag{12}$$

$$PDSE = 100 \times \left(\frac{Z_{\text{support/product,old}} - Z_{\text{support/product,new}}}{Z_{\text{support/product,old}}} \right) \tag{13}$$

As results of the second and third ALB problems in **Table 3**, dragging arm and frame assembly lines arranged by factory and optimized by GA, TS, CS and ACS are omitted because they have a similar pattern to those of the first ALB problem shown in **Figure 7**-**Figure 11** and **Table 4**-**Table 8**. Referring to **Table 3**, the ACS provides superior results to other algorithms and a factory. The workload variance obtained by the ACS is less than that

Table 2. Lists of search spapces.

ALB problems	Search spaces
Tuning Disk	$S_1 \in [2, 15]$; $S_2 \in [2, 15]$; $S_3 \in [10, 30]$; $S_4 \in [2, 15]$; $S_5 \in [10, 25]$
Dragging Arm	$S_1 \in [2, 10]$; $S_2 \in [10, 30]$; $S_3 \in [2, 10]$; $S_4 \in [2, 20]$; $S_5 \in [10, 20]$; $S_6 \in [2, 15]$
Frame	$S_1 \in [5, 10]$; $S_2 \in [10, 20]$; $S_3 \in [5, 20]$; $S_4 \in [15, 30]$; $S_5 \in [10, 20]$

Table 3. Results of ALB problems.

ALB#1: Turning Disk				
Methods	w_v	T_{id} (min.)	E (%)	Search Time (sec.)
Factory	1,793.10	302.02	60.35	-
GA	457.03	302.02	75.11	510.64
TS	333.03	302.02	76.17	342.58
CS	293.09	302.02	77.02	248.26
ACS	249.28	302.02	81.42	221.45
ALB#2: Dragging Arm				
Methods	w_v	T_{id} (min.)	E (%)	Search Time (sec.)
Factory	1,286.60	430.71	41.65	-
GA	134.18	430.71	70.82	522.54
TS	122.12	430.71	77.64	397.23
CS	88.59	430.71	79.64	348.67
ACS	72.89	430.71	81.39	291.15
ALB#3: Frame				
Methods	w_v	T_{id} (min.)	E (%)	Search Time (sec.)
Factory	38,119.43	1,925.43	40.93	-
GA	3,534.78	1,925.43	74.45	566.14
TS	2,430.51	1,925.43	74.45	497.33
CS	2,257.49	1,925.43	77.23	375.36
ACS	1,563.12	1,925.43	78.51	292.48

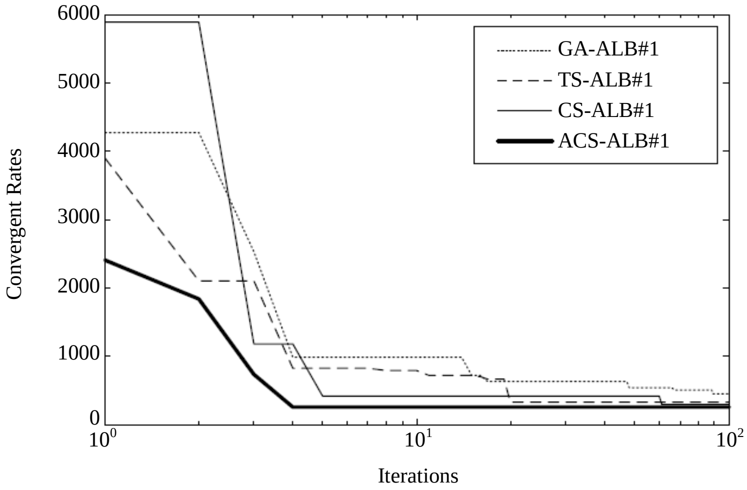


Figure 4. Convergent rate of the first ALB problem.

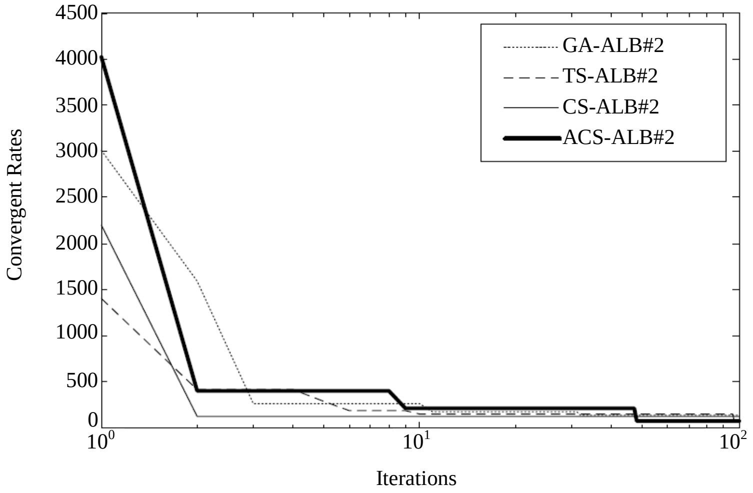


Figure 5. Convergent rate of the second ALB problem.

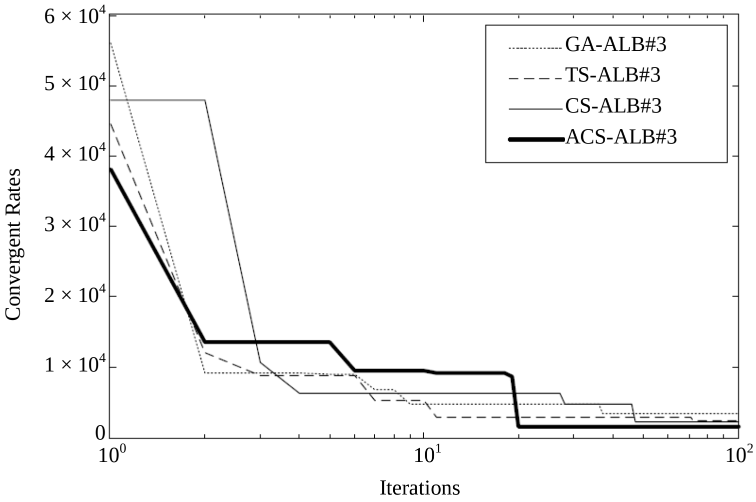


Figure 6. Convergent rate of the third ALB problem.

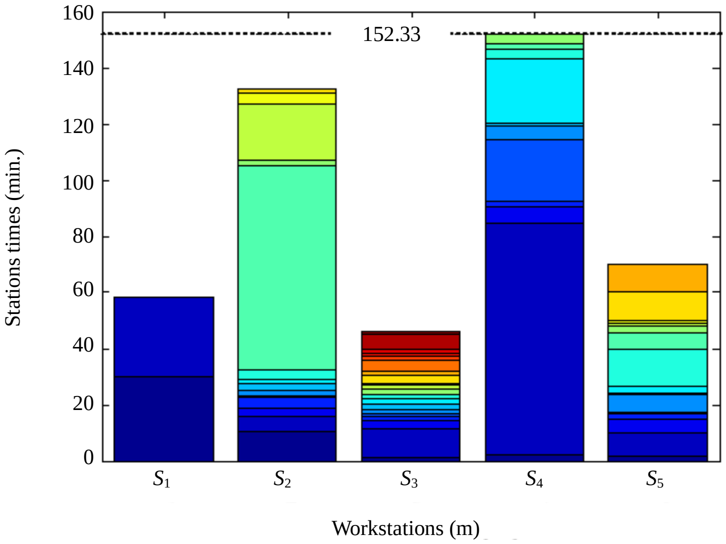


Figure 7. Turning disk assembly line by factory.

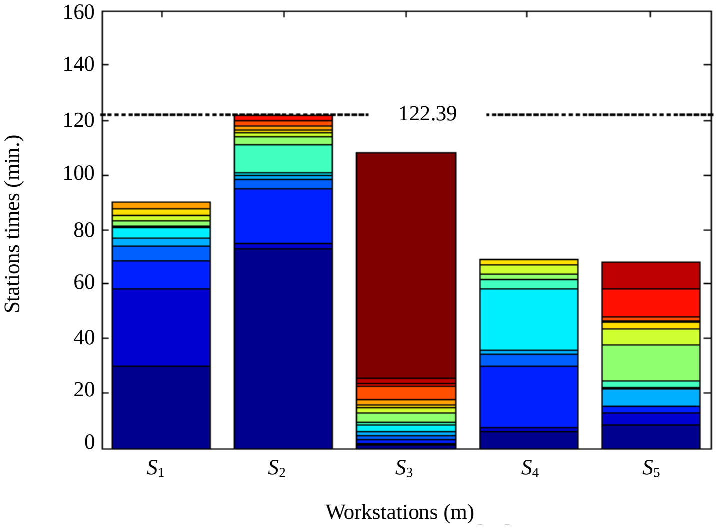


Figure 8. Turning disk assembly line by GA.

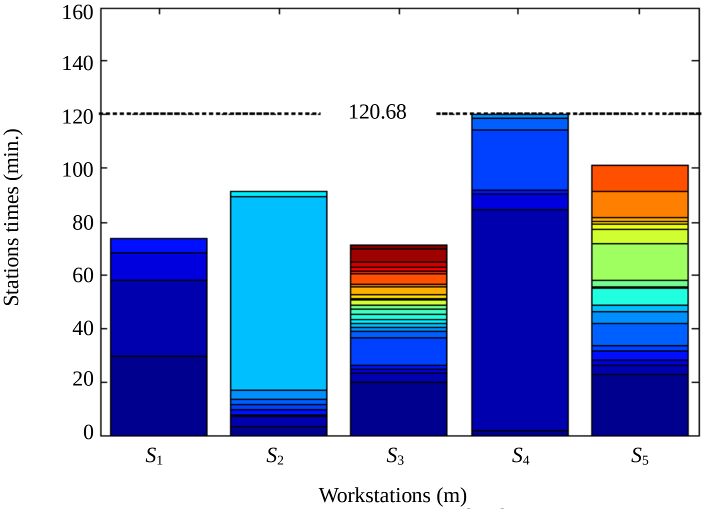


Figure 9. Turning disk assembly line by TS.

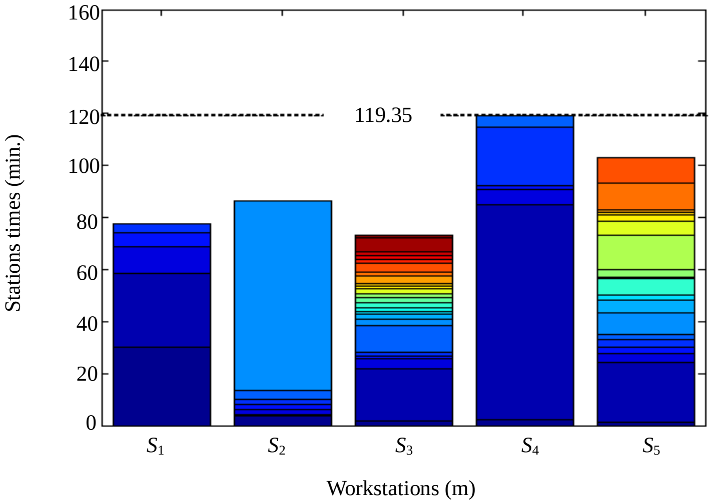


Figure 10. Turning disk assembly line by CS.

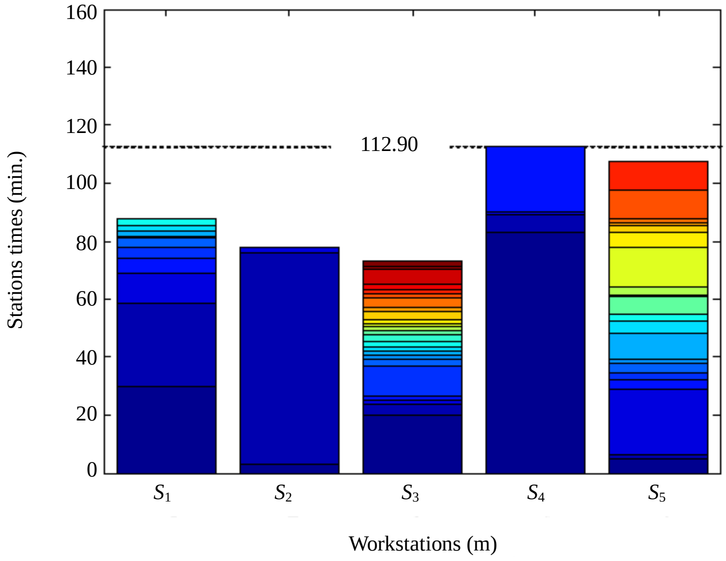


Figure 11. **Turning disk assembly line by ACS.**

Table 4. **Tasks for turning disk assembly line by factory.**

Work-Station (*m*)	Tasks assigned for each workstation	Station Time (min.)	Idle Time (min.)
1	1,2	58.44	93.89
2	3,4,5,6,7,8,9,10,11,12,13,14,15,16	132.42	19.91
3	17,18,19,20,21,22,23,24,25,26,27,28,29,30,31,32,33,34,35,36,37	46.31	106.02
4	38,39,40,41,42,43,44,45,46,47,48	152.33	0.00
5	49,50,51,52,53,54,55,56,57,58,59,60,61,62,63	70.13	82.20

The total idle time (T_{id}) = 303.02 min., The workload variance (w_v) = 1,793.10, The line efficiency (E) = 60.35%.

Table 5. **Tasks for turning disk assembly line by GA.**

Work-Station (*m*)	Tasks assigned for each workstation	Station Time (min.)	Idle Time (min.)
1	1,2,3,4,5,6,7,8,9,10,11	90.79	61.54
2	12,13,14,15,16,17,18,19,20,21,22,23,24	122.39	29.94
3	25,26,27,28,29,30,31,32,33,34,35,36,37,38,39	108.84	43.49
4	40,41,42,43,44,45,46,47,48,49	69.33	83.00
5	50,51,52,53,54,55,56,57,58,59,60,61,62,63	68.28	84.05

The total idle time (T_{id}) = 303.02 min., The workload variance (w_v) = 457.03, The line efficiency (E) = 75.11%.

Table 6. **Tasks for turning disk assembly line by TS.**

Work-Station (*m*)	Tasks assigned for each workstation	Station Time (min.)	Idle Time (min.)
1	1,2,3,4	74.04	78.29
2	5,6,7,8,9,10,11,12,13	91.73	60.60
3	14,15,16,17,18,19,20,21,22,23,24,25,26,27,28,29,30,31,32,33,34,35,36,37	71.40	80.93
4	38,39,40,41,42,43,44	120.68	31.65
5	45,46,47,48,49,50,51,52,53, 54,55,56,57,58,59,60,61,62, 63	101.78	50.55

The total idle time (T_{id}) = 303.02 min., The workload variance (w_v) = 333.03, The line efficiency (E) = 76.17%.

Table 7. **Tasks for turning disk assembly line by CS.**

Work-Station (*m*)	Tasks assigned for each workstation	Station Time (min.)	Idle Time (min.)
1	1,2,3,4,5	77.53	74.80
2	6,7,8,9,10,11,12	86.45	65.88
3	13,14,15,16,17,18,19,20,21,22,23,24,25,26,27, 28,29,30,31,32,33,34,35,36,37	73.19	79.14
4	38,39,40,41,42,43	119.35	32.98
5	44,45,46,47,48,49,50,51,52,53,54,55,56,57,58,59,60,61,62,63	103.11	49.22

The total idle time (T_{id}) = 303.02 min., The workload variance (w_v) = 293.09, The line efficiency (E) = 77.02%.

Table 8. **Tasks for turning disk assembly line by ACS.**

Work-Station (*m*)	Tasks assigned for each workstation	Station Time (min.)	Idle Time (min.)
1	1,2,3,4,5,6,7,8,9,10	87.88	64.45
2	11,12,13	77.89	74.44
3	14,15,16,17,18,19,20,21,22,23,24,25,26,27,28,29, 30,31,32,33,34,35,36,37,38	73.32	79.01
4	39,40,41,42	112.90	39.43
5	43,44,45,46,47,48,49,50,51, 52,53,54,55,56, 57,58,59,60, 61,62,63	107.64	44.69

The total idle time (T_{id}) = 303.02 min., The workload variance (w_v) = 249.28, The line efficiency (E) = 81.42%.

Table 9. **Yearly results of energy resource management of ALB problems.**

ALB#1: Turning Disk

Methods	Number of products	Z_{total} (MWh)	$Z_{total/product}$ (kWh)	*PDTE* (%)	Z_{main} (MWh)	$Z_{main/product}$ (kWh)	$Z_{support}$ (MWh)	$Z_{support/product}$ (kWh)	*PDSE* (%)
Factory	866.54	92.54	106.79	-	53.43	61.66	39.11	45.14	-
GA	1,078.52	105.61	97.92	8.31	66.50	61.66	39.11	36.26	19.65
TS	1,093.80	106.55	97.41	8.78	67.44	61.66	39.11	35.76	20.78
CS	1,105.99	107.30	97.02	9.15	68.19	61.66	39.11	35.36	21.65
ACS	1,169.18	111.20	95.11	10.94	72.09	61.66	39.11	33.45	25.88

ALB#2: Dragging Arm

Methods	Number of products	Z_{total} (MWh)	$Z_{total/product}$ (kWh)	*PDTE* (%)	Z_{main} (MWh)	$Z_{main/product}$ (kWh)	$Z_{support}$ (MWh)	$Z_{support/product}$ (kWh)	*PDSE* (%)
Factory	1,073.00	83.00	77.36	-	43.90	40.91	39.11	36.45	-
GA	1,824.46	113.75	62.35	19.41	74.64	40.91	39.11	21.44	41.19
TS	2,000.30	120.95	60.46	21.84	81.83	40.91	39.11	19.55	46.36
CS	2,051.92	123.06	59.97	22.49	83.95	40.91	39.11	19.06	47.71
ACS	2,096.90	124.90	59.56	23.01	85.79	40.91	39.11	18.65	48.83

ALB#3: Frame

Methods	Number of products	Z_{total} (MWh)	$Z_{total/product}$ (kWh)	*PDTE* (%)	Z_{main} (MWh)	$Z_{main/product}$ (kWh)	$Z_{support}$ (MWh)	$Z_{support/product}$ (kWh)	*PDSE* (%)
Factory	202.47	77.55	382.99	-	38.43	189.83	39.11	193.17	-
GA	368.25	109.02	296.03	22.71	69.90	189.83	39.11	106.21	45.02
TS	368.25	109.02	296.03	22.71	69.90	189.83	39.11	106.21	45.02
CS	372.33	109.79	294.87	23.01	70.68	189.83	39.11	105.04	45.62
ACS	388.37	112.83	290.53	24.14	73.72	189.83	39.11	100.71	47.87

obtained by GA, TS and CS, while *E* obtained by the ACS is the highest. Productivity, total energy consumption, *PDTE* and *PDSE* can be yearly calculated and also summarized in **Table 9**.

Referring to **Table 9**, results of energy resource management of all three ALB problems are yearly summarized. It was found that productivity of all lines is significantly increased. The highest productivity of all lines is achieved due to the least workload variance obtained by the proposed ACS. For the first ALB problem once compared with factory, the productivity of 24.46%, 26.23%, 27.63% and 34.93% can be increased by GA, TS, CS and ACS, respectively. For the second ALB problem once compared with factory, the productivity of 70.03%, 86.42%, 91.23% and 95.42% can be increased by GA, TS, CS and ACS, respectively. For the third ALB problem once compared with factory, the productivity of 81.88%, 81.88%, 83.89% and 91.82% can be increased by GA, TS, CS and ACS, respectively. These cause total and main energies per year are increased proportionally, while supporting energy is unchanged. In contrast, once considering energy per product, it was found that total and supporting energies per product are decreased proportionally, while main energy is unchanged. As results in **Table 9**, for the first ALB problem once compared with factory, the total energy per product of 8.31%, 8.73%, 9.15% and 10.94% can be decreased by GA, TS, CS and ACS, respectively. For the second ALB problem once compared with factory, the total energy per product of 19.41%, 21.84%, 22.49% and 23.01% can be decreased by GA, TS, CS and ACS, respectively. For the third ALB problem once compared with factory, the total energy per product of 22.71%, 22.71%, 23.01% and 24.14% can be decreased by GA, TS, CS and ACS, respectively. In addition, for the first ALB problem once compared with factory, the supporting energy per product of 19.65%, 20.78%, 21.65% and 25.88% can be decreased by GA, TS, CS and ACS, respectively. For the second ALB problem once compared with factory, the supporting energy per product of 41.19%, 46.36%, 47.71% and 48.83% can be decreased by GA, TS, CS and ACS, respectively. For the third ALB problem once compared with factory, the supporting energy per product of 45.02%, 45.02%, 45.62% and 47.87% can be decreased by GA, TS, CS and ACS, respectively. It can be noticed that for all problems, the maximum *PDTE* and the maximum *PDSE* are achieved by the ACS.

6. Conclusion

Optimization of energy resource management for assembly line balancing (ALB) problems in a car factory by the adaptive current search (ACS) has been proposed in this paper. With proposed optimization approach, assembly lines are balanced in order to optimize their energy resources management. The ACS has been used to address the number of tasks assigned for each workstation. Three selected real-world ALB problems, *i.e.* turning disk, dragging arm and frame assembly lines, from a specific car factory are conducted. By comparison, the ACS outperforms genetic algorithm (GA), tabu search (TS) and current search (CS). Results obtained by the ACS are superior to those obtained by other algorithms. The workload variances of all lines obtained by the ACS are less than those obtained by GA, TS and CS, whereas the line efficiencies of all lines achieved by the ACS are the highest values among those algorithms. In sense of energy resource management optimization, it was found that the least workload variances obtained by the ACS caused the highest productivities of all lines. The maximum percent of decreased total energy per product and the maximum percent of decreased supporting energy per product are also successfully achieved due to the least workload variance obtained by the proposed ACS. It can be concluded that the ACS is one of the most efficient algorithms and can be an alternative to optimize the energy resource management problems.

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Appendix

Table A. Details of the turning disk assembly line.

No.	Descriptions	Task Times (min.)	Precedent Tasks
1.	Cutting iron sheets by gas	30.00	-
2.	Grinding work pieces	28.44	1
3.	Blowing JIG part	10.40	2
4.	Placing L/R reinforcement beams on JIG and locked by C-clamp	5.20	3
5.	Placing H-beam frame of 1,570 mm. on L/R reinforcement beams	3.49	4
6.	Spacing between 2 H-beam frames of 880 mm.	3.75	5
7.	Tightening H-beam and reinforcement beam frame by clamp	0.51	6
8.	Welding H-beam frame and reinforcement beam	1.77	7
9.	Assembling H-beam frame of 945 mm. on JIG both front and back sides	2.07	8
10.	Assembling hot rolled rails steel of 945 mm. on JIG	2.25	9
11.	Welding H-beam frame of 945 mm. and hot rails steel with frame of 1,570 mm	2.91	10
12.	Full welding entire front-down parts	73.19	11
13.	Welding splice angle plate into tuning desk frame	1.79	12
14.	Full welding entire front parts	20.17	13
15.	Eroding all welding line	3.53	14
16.	Moving assembled tuning desk frame into haven by crane	1.39	15
17.	Moving assembled tuning desk frame on JIG	1.20	16
18.	Installing BRKT, holding pincers and BRKT and holding dragging arm	10.35	17
19.	Placing L-R rear hangers and locked by C-clamp	2.57	18
20.	Checking BRKT and inside pincer perpendicular to tuning desk by steel angle	1.55	19
21.	Checking space between BRKT and inside pincer of 900 mm.	1.20	20
22.	Welding BRKT and L-R pincers	1.45	21
23.	Placing and welding steel pipe to pincer of 895 mm.	2.10	22
24.	Placing L-R front hangers and locked by C-clamp	1.90	23
25.	Checking BRKT and outside pincer perpendicular to tuning desk by steel angle	1.35	24
26.	Checking space between 2 sides steel pipe of 760 mm.	0.13	25
27.	Welding BRKT and L-R pincers	1.62	26
28.	Welding both 2 sides of front perpendicular place	1.27	27
29.	Welding steel pipe of 800 mm. for front pincer to front hanger pipe	1.33	28
30.	Placing bush PULL BRKT ASS’Y on tuning desk	2.44	29
31.	Threading steel shaft via bush, BRKT and steel pipe with space of 816 mm.	1.55	30
32.	Tightening both sides of PULL BRKT ASS’Y by hammer	3.55	31
33.	Welding PULL BRKT ASS’Y into front hanger and tuning desk frame	1.47	32
34.	Full welding of front side of L-R PULL BRKT ASS’Y	1.38	33
35.	Moving threading steel shaft out of PULL BRKT ASS’Y	1.57	34
36.	Welding reinforcement beam of 650, 420 and 200 mm. into tuning desk frame	5.03	35
37.	Moving assembled tuning desk frame into haven by crane	1.30	36
38.	Moving assembled tuning desk frame on JIG	1.92	37
39.	Full welding entire front-down tuning desk frame	82.93	38
40.	Eroding all welding line	5.87	39
41.	Inclining and turning JIG to left side of tuning desk	1.45	40
42.	Full welding entire left-side tuning desk frame	22.65	41
43.	Eroding all welding line	4.53	42
44.	Inclining and turning JIG to right side of tuning desk	1.33	43
45.	Full welding entire right-side tuning desk frame	22.65	44
46.	Eroding all welding line	3.57	45
47.	Turning JIG to original place and unlocking clamp	2.28	46
48.	Moving assembled tuning desk frame into haven by crane	3.15	47
49.	Moving assembled tuning desk frame on JIG	1.85	48
50.	Grinding welding line of splice angle plate (RIG) at 4 angles	8.43	49
51.	Measuring the center point of tuning desk and placing holed guide on frame	4.55	50
52.	Drilling 8 holes according to guide by drill of 5 mm.	2.37	51
53.	Moving holed guide out of frame to broaching	0.12	52
54.	Broaching 8 holes of 18 mm. by magnetic drill	6.28	53
55.	Grinding all 8 holes	0.37	54
56.	Lifting and placing tuning desk by crane onto tuning desk frame	2.58	55
57.	Holding screws M 16 × 50 mm. at 8 holes and tightening them	13.55	56
58.	Welding splice plate and elephantiasis pipe clamp to H-beam frame	5.50	57
59.	Eroding all welding line	2.21	58
60.	Grinding welding line of splice plates	0.85	59
61.	Moving assembled tuning desk frame into haven by crane	1.47	60
62.	Checking assembled tuning desk	10.00	61
63.	Moving assembled tuning desk to next station	10.00	62