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IFAC PapersOnLine 51-11 (2018) 669–674

Heuristic methods to consider rest allowance into assembly balancing problem

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Abstract: This study incorporates human energy expenditure and the related rest allowance into a SALBP-2. During last years, the impact of human factors on the assembly line design has grown up and ergonomic restrictions, worker skills, physical and psychological conditions have been considered in the assembly balancing. In this work, the human energy expenditure is applied. For this purpose, three heuristic methods are here proposed and compared in order to underline the effect of rest allowance in the balancing problem. A numerical example is used to show and discuss the differences between the three methods.

Keywords: SALBP-2, Energy Expenditure, Heuristic Method, Ranked Positional Weights Method, Rest Allowance.

1. INTRODUCTION AND BACKGROUND

Manual assembly lines are special flow-line production system (Scholl, 1999). They consist in several successive workstations in which manual assembly tasks are performed by skilled operators. In a manual assembly line, human conditions have a high impact on the final productivity. As defined by Battini et al. (2011), there is a correlation between the assembly system design and the ergonomics level of workstations. In the last years, a lot of researches have focused on the optimisation of the operator ergonomic conditions at the workstation. Otto and Battaïa (2017) have recently provided an overview of the existing optimization approaches to assembly line balancing that consider physical ergonomic risks. Following their research, it is possible to note that there are a lot of researches on which ergonomic risks are evaluated through NIOSH, RULA, REBA, OCRA, EAWS but little attention is given to the energy expenditure method (EnerExp) (Garg et al. 1978). EnerExp estimates metabolic rates for material manual handling tasks and it considers different parameters as workers, task duration, load weight to name a few. To the best of our knowledge the first research focused on the integration between EnerExp and assembly balancing problem was made by Gunther et al. (1983). After this research EnerExp has been considered by Battini et al. (2016) whom proposed two different models. The first one is a multi-objective model that minimizes EnerExp and the cycle time of the assembly line. The second one transforms energy expenditure in a rest time provided by Rohmert (1973) in order to obtain a single-objective model. Recently, a new mixed-integer model has been developed by Battini et al. (2017) to evaluate the ergonomic impact, in term of energy expenditure, in synchronised operations of the assembly line and supermarket area. Through their study it is possible to note that integrated planning may reduce the ergonomic risks at workplaces and the number of required workers simultaneously. Akyol and Baykasoğlu (2016) minimized the cycle time of the line considering simultaneously the worker-to-station assignment and assembly balancing. They included also some restriction in term of operators' ergonomic conditions.

In this work, we aim to analyse three different ways to integrate energy expenditure within a heuristic method to balance an assembly line. We consider a SALBP-2 as, in this way, there is the possibility to evaluate the impact energy expenditure and the related rest allowance could have in the final cycle time. In simple assembly line balancing type 2 (SALBP-2) the number of station is given and the objective function is to minimize the cycle time. Generally, SALBP-2 leads to the maximization of the production rate of an existing assembly line (Scholl and Voß, 1997). These types of problems are generally analyzed when there are changes in the production process or in the demand of some products.

Through this work, we want to define the minimum cycle time taking into account the task time and the operator energy expenditure linked to each task. We compare three methods that consider rest allowance in different manner. In this way it is possible better understand the impact energy expenditure, in term of rest allowance, could have into the assembly balancing problem. In order to minimize only the cycle time with rest allowance considerations, we transform the energy expenditure in a rest allowance as defined by Price (1990). Following what was defined by Price (1990), each operator has an acceptable work level which could be considered equal to 4.3 kCal/min. In order to define the work level of each task or a set of tasks we use the energy/time ratio as defined in Battini et al. (2016). With this index we can understand, for the task under consideration, if the operator exceeds the acceptable work level or not. If this happens, it is necessary to evaluate the recovery time and in this way the total time of the task increases. We want to evaluate the impact of the rest allowance on the cycle time when we consider the energy expenditure linked to a single task or a set of tasks. In fact, there is the possibility that a task with a high time and a small energy expenditure, that does not require a rest allowance can balance a task that has a lower time but a higher energy expenditure,

10.1016/j.ifacol.2018.08.395

that requires rest allowance. In this way, we consider energy expenditure only if it is necessary and we avoid having a higher cycle time when it is not necessary. The first method, that is also the simplest one, consider ergonomic condition after the balancing phase while others two evaluate in a different way rest allowance during the task allocation phase. The remainder of this paper is composed of following sections. Section 2 presents the initial framework and the three-different method. The new heuristic method is described in paragraph 2.3. In section 3, the case study and final results are explained. Finally, in section 4, the conclusion and future researches are presented.

2. METHODS DESCRIPTION

In this section, three heuristic procedures for SALBP-2 are provided and compared. They are all based on the ranked positional weights method (RPW) concept and task energy expenditure, in term of rest allowance, is considered in different ways. The first method considers the task time without rest allowance to assign tasks to a workstation and in a second phase the total time of each workstation is calculated considering the total energy expenditure linked to the workstation. In the second method each task time is incremented by its rest allowance and then RPW procedure is applied. The third method evaluates the rest allowance and eventually the new total time of each station whenever a new task is assigned to the station under study, in this case rest allowance is associated to a set of tasks and not only to a single task.

As defined in Klein and Scholl (1996) solving SALBP-2 includes two main steps which have to be executed simultaneously. The first step is to determine the minimum cycle time and the second one is to assign the task to the station considering the cycle time defined in the first step. This procedure could be represented as an iterative procedure. For this reason, it is necessary to define a lower bound for the cycle time and start with this value the resolution of the balancing problem. In the sequel, a task-oriented procedure (Hackman et al., 1989) is proposed and tasks are ranked according to a descending positional weight. The aim is to minimize the cycle time considering both time and human energy expenditure of each task.

We have a list of *n* tasks and *m* stations. For each task, the following data are noted:

- task time [s], *t(j)*;
- human energy expenditure [kCal/s], *e(j)*;
- $P_j(\text{resp.} F_j)$: set of tasks which directly precede (follow) task j in the precedence graph;
- $P'_j(\text{resp.} F'_j)$: set of all tasks which precede (follow) task j in the precedence graph;

Through these two sets of data it is possible to define, for each task, the following data:

- Energy-Time Ratio (Battini et al, 2015),

$$ET(j) = \frac{e(j)}{t(j)} * 60 \quad (1)$$

- Rest Allowance (Price, 1990)

$$RA(j) = \begin{cases} 0 \text{ if } \mathrm{ET(j)} \le 4.3 \\ \dfrac{ET(j) - 4.3}{4.3 - 1.86} \text{ otherwise} \end{cases} \quad (2)$$

The Rest Allowance represents the percentage of recovery, in term of time, for an operator after performing a task and it is a way to consider the energy expenditure in the task time.

Considering the RA, the final task time becomes:

$$t'(j) = t(j) * (1 + RA(j)) \qquad \forall j = 1,..,n \quad (3)$$

This value could be equal or larger than the initial task time *t(j)*.

For each task it is now possible to define these others two data:

- $tp'_j = t'(j) + \sum_{h \in P_j'} t'(h)$ (4)

  which is defined as the total time of all tasks that precede task j;
- $tf'_j = t'(j) + \sum_{h \in F_j'} t'(h)$ (5)

  which is defined as the total time of all tasks that follow task j.

If the Rest Allowance is not considered into the task time formulas (4) and (5) become:

- $tp_j = t(j) + \sum_{h \in P_j'} t(h)$ (6)
- $tf_j = t(j) + \sum_{h \in F_j'} t(h)$ (7)

2.1 First method

In this first model, we consider only the task time during the balancing phase while energy expenditure is considered in the last instance. As energy expenditure is not considered we consider (6) and (7) to determinate total time of all tasks that precede (resp. follow) task j.

In order to start the heuristic model, we define the Lower Bound as:

$$LB_1 = \left\lceil \max(\max(t(j); (\textstyle\sum_{j=1}^{n} t(j)) / m)) \right\rceil \quad (8)$$

Initially, cycle time, c, is equal to LB_1 and the following steps are executed:

Step 1: Calculate (Scholl, 1999):

- $E_j(c)$: earliest station of task j for cycle time c;
- $L_j(c)$: latest station of task j for cycle time c;
- $SI_j(c) = \left[E_j(c); L_j(c)\right]$: station interval of task j for cycle time c;

Step 2: List the tasks in increasing order of the $E_j(c)$ and descending order of tf_j;

Step 3: Consider the set of available tasks for each workstation *i=1,…,m*. Initialize $t_{sum}(i) = 0$ which is the initial station time of the station *i;*

Step 4: Assign to station i all tasks belonging to $\Omega = \{j = 1,..,n \mid E_j(c)=L_j(c)\}$;

Step 5:

- Define $t_{sum}(i) = \sum_{j\in\Omega} t(j)$ (12)
- Define $I_i(c) = c - t_{sum}(i)$ (13)

Step 6: Assign the others available tasks to station i in decreasing order of their tf_j value and repeat step 5 for each task assigned.

Note that a new station is opened if $I_i(c)$ becomes less or equal to 0 while the cycle time is increased by 1 and the algorithm is again executed in the following cases:

- $I_i(c) \le 0$ and there are some tasks which must be assigned to station i;
- Some tasks are not assigned to a station.

The algorithm stops when every task is assigned to a station and for each station, $I_i(c)$ is equal or greater than 0.

After this first phase for each station it is possible to define the ET value defined as follow:

$$ET(i) = \frac{\sum_j e_i(j)}{\sum_j t_i(j)} * 60 \quad (14)$$

In this way, RA(i) is calculated and the total time of station i becomes:

$$t"_{sum}(i) = \begin{cases} t_{sum}(i) \text{ if ET(i)} \le 4.3 \\ t_{sum}(i) * (1 + RA(i)) \text{ otherwise} \end{cases} \quad (15)$$

In this model, a first cycle time is defined but it could not be the final cycle time. Indeed, if the energy/time ratio in a station is greater than 4.3 rest allowance is calculated and for this reason the total time of a station increases. In this way, the final cycle time becomes:

$$CT = \max(c; \max(t"_{sum}(i))) \quad (16)$$

2.2 Second method

With this method, the energy expenditure is included directly in each task time through the rest allowance define in (2). In this way, each task time is equal to $t'(j)$ as defined in (3).

The lower bound is defined as follow:

$$LB_2 = \left\lceil \max(\max(t'(j); (\sum_{j=1}^{n} t'(j)) / m \right\rceil \quad (17)$$

The initial cycle time, c, is equal to LB_2 the define in (17).

To assign a task to a station the same procedure used in Section 2.1 is used but in this case, there are some changes. The first one is linked to Step 1, as the calculation of the earliest and latest station considers $t'(j)$. The second one is linked to step 5 as:

$$t'_{sum}(i) = \sum_j t'(j) \quad (18)$$

The other steps remain the same.

The cycle time is incremented by 1 and the procedure is repeated until all tasks are assigned to a station avoiding cycle time violations.

2.3 Third method

This is a new heuristic approach to consider human energy expenditure and the related rest allowance directly into assembly line balancing problem. With this approach, initially, the cycle time is equal to LB_1 defined in (17) and the following steps are executed:

Step 1: Calculate:

- $E'_j(c) = \left\lceil (t'(j) + \sum_{h\in P_{j'}} t'(h)) / c \right\rceil$: (19)
  earliest station of task j for cycle time c;
- $L'_j(c) = m + 1 - \left\lceil (t'(j) + \sum_{h\in F_{j'}} t'(h)) / c \right\rceil$ (20)
  latest station of task j for cycle time c;
- $SI'_j(c) = \left[E'_j(c); L'_j(c) \right]$: station interval of task j for cycle time c;

Step 2: List the tasks in increasing order of the $E'_j(c)$ and descending order of tf'_j ;

Step 3: Consider the set of available tasks for each workstation $i=1,\ldots,m$. Initialize $t_{sum}(i) = 0$ and $e_{sum}(i) = 0$ which are respectively the station time of the station i and the total energy expenditure of the station i;

Step 4: First the tasks that have $E'_j(c) = L'_j(c)$ are assigned to the station i;

Step 5:

- Define $t_{sum}(i) = \sum_j t(j)$ (21)
- Define $e_{sum}(i) = \sum_j e(j)$ (22)
- Calculate ET(i) considering $t_{sum}(i)$ and $e_{sum}(i)$;
- Calculate RA(i) and the new $t"_{sum}(i) = t_{sum}(i) * (1 + RA(i))$ (23)
- Define the remaining available time of the station i as $I_i(c) = c - t"_{sum}(i)$ (24)

Step 6: Assigned the others available tasks to station i in decreasing order of their tf'_j value and repeat step 5 for each task assigned.

If there are some tasks not assign to a station the cycle time is increased by 1 and the algorithm stops when all tasks are associated with a station without exceeding cycle time.

Through this model, there is a balancing between the energy expenditure of the tasks already assigned to a station and the available tasks. In step 5 $t_{sum}(i)$ and $e_{sum}(i)$ are calculated to evaluate ET step by step every time a task is assigned to a station. In this way, it is possible considering RA only in the case on which the ET value associated with the station is greater to 4.3. Following this method, the cycle time should be less or at least equal to the one obtained considering the two more-simple algorithms proposed in section 2.1 and 2.2.

3. NUMERICAL EXAMPLES AND DISCUSSION

In this section, a numerical example is presented. We consider the precedence graph and the task time presented in Battini et al. 2015. There are 17 tasks to perform in 4 stations. As explained before the aim of this paper is to propose a heuristic method for SALPB-2. For the energy expenditure value of each task, we consider the set of data shown in Fig. 1. The Energy-Time ratio, in this case, is equal to 4.45. In order to better understand the impact of ET on final results in section 3.4. is reported the cycle time obtained applying the three methods for different value of ET.

TASK	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
TIME [s]	24	46	13	7	25	15	5	38	11	80	85	25	60	65	45	25	16
ENERGY [kCal]	1.11	4.45	0.37	0.52	2.82	1.78	0.96	1.85	0.82	5.93	6.3	1.85	3.41	4.82	3.34	1.85	1.19

Fig. 1. Input data

3.1 Data and results with the application of the first method

This procedure considers energy expenditure only in the last phase. In this model, t_{P_j}, t_{F_j} and c are calculated considering t(j) (Table 1). In this case, the initial cycle time is equal to 147 seconds but only with c=150 seconds all tasks are assigned to a station in a correct way. Using the RPW method the final solution is presented in Table 2.

Table 1. Task times, total time of previous and following tasks

TASK	t(j)	tp_j	tf_j
A	24	24	585
B	46	70	460
C	13	83	414
D	7	31	408
E	25	49	441
F	15	64	416
G	5	29	406
H	38	62	450
I	11	73	412
J	80	264	376
K	85	349	296
L	25	209	236
M	60	434	146
N	65	439	151
O	45	544	86
P	25	569	41
Q	16	585	16

Table 2. Final assembly line balancing with RPW method

Station	Assigned tasks	t_{sum}
1	A, B, H, E, F	148
2	C, I, D, G, J, L	141
3	K, N	150
4	M, O, P, Q	146

We consider the energy expenditure after the balancing. In fact, for each station, we define the total energy associated with a station and we calculated the new time of each station considering the rest allowance. Doing this, the final cycle time is greater or at least equal to the initial cycle time 150 seconds. In Table 3, the total time, total energy, rest allowance and new station time are proposed. In this case, the final cycle time is equal to 182.55 seconds.

Table 3. Final cycle time with human energy expenditure considerations

Station	Assigned tasks	t_{sum}	e_{sum}	ET	RA	t''_{sum}
1	A, B, H, E, F	148	12.01	4.87	0.23	182.55
2	C, I, D, G, J, L	141	10.45	4.45	0.06	149.60
3	K, M	150	11.12	4.45	0.06	159.15
4	N, O, P, Q	146	9.79	4.02	0	146

3.2 Data and results with the application of the second method

Through this method, we consider directly t'(j) as defined in (3) in the phase related to assigning a task to a station. Considering Table 4. the ET(j) value is calculated for each task and if it is greater than 4.3 the related Rest Allowance is defined. In this way, a new final time t'(j) is obtained as defined in (3). With the new task times, the initial cycle time is defined and also the t_{P_j} and t_{F_j} for j=1,…,n.

Table 4. Task time with rest allowance considerations

Task	t(j)	ET	RA	t'(j)	tp'_j	tf'_j
A	24	2.78	0.00	24.00	24.00	692.66
B	46	5.80	0.62	74.33	98.33	509.12
C	13	1.71	0.00	13.00	111.33	434.79
D	7	4.45	0.06	7.43	31.43	429.22
E	25	6.76	1.01	50.23	74.23	504.34
F	15	7.12	1.15	32.32	106.55	454.12
G	5	11.57	2.98	19.89	43.89	441.68
H	38	2.93	0.00	38.00	62.00	471.46
I	11	4.45	0.06	11.67	73.67	433.46
J	80	4.45	0.06	84.88	355.75	395.27
K	85	4.45	0.06	90.18	445.93	310.39
L	25	4.45	0.06	26.52	297.39	246.73
M	60	3.41	0.00	60.00	532.45	151.24
N	65	4.45	0.06	68.96	541.42	160.21
O	45	4.45	0.06	47.74	649.16	91.24
P	25	4.45	0.06	26.52	675.69	43.50
Q	16	4.45	0.06	16.98	692.66	16.98

The initial cycle time is equal to 174 seconds but it is not a sufficient time and some restrictions are violated, in particular, some tasks are not assigned to a station includes in the range $SI_j(c)$.

It is necessary to increase it by one until 187 seconds which represents the minimum cycle time. With this cycle time, the solution is that one illustrated in Table 5.

Table 5. Assembly line balancing applying the 2nd method

Station	Assigned tasks	t'_{sum}	t''_{sum}
1	A, B, E, H	186.56	150.23
2	F, G, C, I, D, J	169.19	155.4
3	L, K, N	185.67	185.67
4	M, O, P, Q	151.24	151.24

3.3 Data and results with the application of the third model

With this algorithm, the first steps are the same of the 2nd algorithm.

Initially, the cycle time is equal to 174 seconds, but some constraints are violated so it is necessary to increase the cycle time until 180 s to assign all tasks to a station. This cycle time represents also the minimum cycle time for this case with 4 stations.

Fig. 2. reports $E'_j(c)$ and $L'_j(c)$ with c=180 seconds. Note that task A must be assigned to station 1 as $E'_1(180) = L'_1(180)$; the same procedure will be applied for task J that must be assigned to station 2 and tasks N, O, P, Q must be assigned to station 4. The other tasks are listed following an increasing order of $E'_j(180)$ and a decreasing order of t'_{F_j} at the same time. We explain step by step the procedure to assign tasks to a station only to the first station. For station 2, 3 and 4 the final results and the tasks assigned are reported in Table 6.

The available tasks for station 1 are: A, B, E, H, F, G, C, I, D, they are listed following the order defined above. Task A is assigned directly to station 1 and $t_{sum}(1) = 24$ while $e_{sum}(1) = 1.10$.

The next step evaluates the RA of the tasks assigned to the station. For this task, RA=0 as ET is less than 4.3. In this way $t''^{(1)}_{sum} = 24$ and $I_i(c) = 180 - 24$.

As $I_i(c)$ is greater than 0 we can assign another task to this station and we choose that one has a greater value of t_{F_j}, in this case, task B. With task B, $t_{sum}(1) = 24 + 46$ while $e_{sum}(1) = 1.10 + 4.39$. In this case, ET becomes equal to 4.77 and as it is greater than 4.3 it is necessary to increase the total time of the station by the rest allowance. For this instance, RA=0.19 and $t''^{(1)}_{sum} = 83.38$.

Following the same procedure tasks, E and H are assigned to station 1. After assigning task H the idle time of station 1 is 29.77. As task F is equal to 15 it is assignable to station 1, so $t_{sum}(1) = 24 + 46 + 25 + 38 + 15$ $e_{sum}(1) = 1.10 + 4.39 + 2.81 + 1.85 + 1.78$, ET(1)=4.86, RA(1)=0.23 and $t''_{sum}(1) = 182.55$. In this case, $t'_{sum}(1)$ is greater than c=180 so the last task must not assign to station 1 and it is necessary to open a new station. In Table 6 final results are reported.

TASK	A	B	E	H	F	G	C	I	D	J	L	K	M	N	O	P	Q
E(j)	1	1	1	1	1	1	1	1	1	2	3	2	3	4	4	4	4
L(j)	1	2	2	2	2	2	2	2	2	2	3	3	4	4	4	4	4

Fig. 2. Earliest and latest station for each task with a cycle time equal to 180 s.

Table 6. Final solution with the third method proposed

Station	Assigned tasks	t_{sum}	e_{sum}	ET	RA	t''_{sum}
1	A, B, E, H	133	10.23	4.61	0.13	150.23
2	F, G, C, I, D, J	131	10.38	4.75	0.19	155.4
3	L, K, M	170	11.57	4.08	0	170
4	N, O, P, Q	151	11.20	4.45	0.06	160.21

3.4 Final results and discussion

In Table 7, we list the final cycle time for each method defined above. With an ET=4.45 the best solution is given with the third method. The main difference with the other two methods is related to the definition of the rest allowance associated with a station. In the first method, rest allowance is calculated after the balancing phase for each station, while in the second one rest allowance is calculated for each task separately. In the third method rest allowance is evaluated each time a task is assigned to a station as a task could require a less energy expenditure than another one and in this way, it would be an automatic reduction of rest allowance into the station.

Table 7. Final comparison

Methodology	Minimum cycle time [s]
1° method	182.55
2° method	185.67
3° method	170

As the last method is also the more difficult to apply it is necessary to understand if it gives always the best solution if compared with the other two methods. The third method requires a major computational time as for each task assigned is necessary evaluate the new rest allowance of the station.

In order to evaluate if the third method always gives the best solution, we have defined different energy expenditure value to obtain different ET value. We have created 18 scenarios in term of energy expenditure while the task time is always the same as the correlation between time and energy. To do this the initial set of energy expenditure has been incremented by a constant value included between [1.1; 2.5] with a step of 0.1. In this way we obtain different ET ratio and different solutions. As it is possible to note in Fig. 3. with different ET value the method that gives the best solution changes. In fact, for ET value lower than 4 the best solution is given by the first method, while for ET value greater than 4 the best solution is given by the third or the second method. In addition, for ET value greater than 5.2 the second and the third method give the same solution.

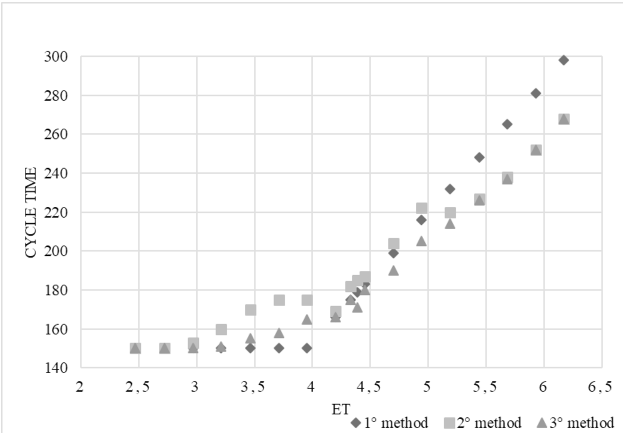

Fig. 3. Comparison between the best solution obtained applying the three methods for different energy/time ratio values.

4. CONCLUSION

Even if lot of research exist on the assembly line balancing, the integration between the necessary time to execute a manual operation and the related human energy expenditure still needs further investigation. In this paper, the authors define a new method to consider task time and the rest allowance (Price, 1990) if the energy expenditure of workers exceeds the recommended limit. The novelty of this approach is linked to the definition of the total time required to perform a set of tasks into a station. This new model has been compared with two more simple models to show the main differences in term of cycle time. The SALBP-2 is considered for this analysis and a numerical case study has been analyzed to better understand the goodness of the new method proposed. Through this work, it is possible to understand that the rest allowance (Price, 1990) for each station depends on task assignment and the related time and energy expenditure. At the same time, the energy/time ratio of all tasks can influence the conclusive results.

Future researches will focus on the correlation between task time and task energy expenditure to evaluate the impact on the final results. An exact model could be developed in order to compare its solution, in term of cycle time, with that one of the heuristic approaches. Furthermore, further dataset will be analyzed to evaluate the robustness of the methods proposed and the impact of energy expenditure, in term of rest allowance, in the final cycle time.

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