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ORIGINAL PAPER

EFFICIENCY IMPROVEMENT OF AUTOMOTIVE ASSEMBLY LINES USING SIMPLE ASSEMBLY LINE BALANCING PROBLEM TYPE-E

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ABSTRACT. Background: An assembly line is a technique used in mass production industries, especially in the automotive industry; it consists of many workstations organized along a conveyor belt system or other material handling equipment. The assembly line balancing problem (ALBP) involves assigning assembly tasks to workstations on the line while meeting optimization goals. It is considered a critical issue in operations management because it directly affects the productivity of the entire manufacturing system.

Methods: Based on the mathematical model previously developed by (Esmaeilbeigi, Naderi, and Charkhgard 2015) for the E-type SALBP problem, we proposed a new model adaptable to the automotive sector. The proposed model uses new feasibility rules and optimizes constraints in order to propose better balancing results and efficiency.

Results: A computational experiment is presented in this article, using the newly developed model to balance an assembly line in an automotive manufacturing plant consisting of 5 workstations.

Conclusions: The experimental results show that the proposed model improved the line efficiency by 15%, which proves that the proposed method has good robustness.

Keywords: Assembly line balancing, Automotive industry, SALBP, SALBP- E, Efficiency.

INTRODUCTION

During the last decade and especially after the COVID-19 pandemic, most of the manufacturing units worldwide have shown a deep concern to improve their business standards to remain in the competitive marketplace (S. E. A. E. El Ahmadi & El Abbadi, 2023; Hussain & Jan, 2019). In addition, balancing assembly lines is one of the pillars of the current industrial revolution.

The objective of the assembly line balancing problem (ALBP) is to assign multiple tasks to a set of workstations such that the precedence relations are satisfied, and some measurements of effectiveness are optimized in order to increase the system productivity (Ahmadi & Abbadi, 2020; S. E. A. El Ahmadi & El Abbadi, 2022).

The ALB problem has frequently been the subject of interest for researchers in recent years. Propositions of solutions to the balancing problems are widely reported in the literature. (Thangavelu & Shetty, 1971) and (Deckro & Rangachari, 1990) proposed mathematical models for solving the problem. (Kilincci & Bayhan, 2006) and (Kilincci, 2010) proposed Petri-net algorithms. (Ponnambalam, Aravindan, et Mogileeswar Naidu 2000), (Lee et al., 2001), (Jiao et al., 2006), (Nearchou, 2008) and (Yeh & Kao, 2009) presented heuristics to resolve the problem, such as bidirectional heuristics. (Sabuncuoglu et al., 2000), (Kim et al., 2009) and (Wang et al., 2012) proposed genetic algorithms as a solution for the SALB problem. (Hong & Cho, 1997), (Baykasoglu, 2006) and (Roshani et al., 2012) adopted the simulated annealing algorithms as a solution to the balancing problem. (Baykasoglu & Dereli, 2008), (Lai & Liu, 2009) and (Fattahi et al., 2011) proposed the ant colony optimization algorithms as a solution.

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(Chica et al., 2010) presented a memetic algorithm as a solution for the problem based on a new local search technique used for the convergence.

(Erel & Sarin, 1998), (EL AHMADI et al., 2019), and (Saif et al., 2014) proposed review articles of the assembly line balancing problems.

There are different kinds of assembly line balancing problems., The basic classification proposed in the literature is the one proposed by (Saif et al., 2014), in which he divides the balancing problems into two major ones as seen in figure 1: simple problems (SALBP) and general problems (GALP).

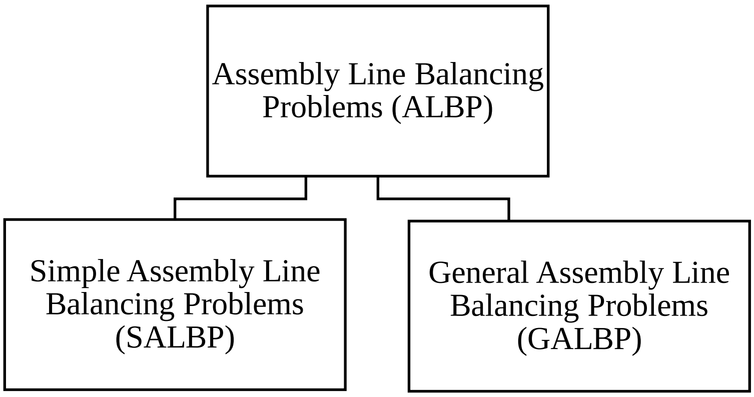

Fig. 1. Classification of Assembly Line Balancing Problems

GALBP refers to General Assembly Line Balancing Problems, which include the complex problems of balancing, namely, the mixed model line balancing problem, U-shaped assembly line problems, robotic assembly line balancing problem, and multi-objective assembly line problems.

SALBP refers to Simple Assembly Line Balancing Problems. It’s the simple version of balancing problems, where the objective is to minimize the cycle time for a fixed number of workstations and vice versa. Researchers in literature proposed to divide the SALB problem into three types SALBP type 1, type 2, and type E (Jirasirilerd et al., 2020), as shown in Table 1:

Table 1. Description of SALBP problems

Problem	Variables to minimize	Variables to maximize	Fixed variables
SALBP type 1	Number of workstations	-	Line cycle time
SALBP type 2	cycle time	-	Number of workstations
SALBP type E	cycle time and Number of workstations	Line Efficiency	-

For the line balancing problems in the automotive sector, the best approach is to minimize simultaneously the cycle time and the number of workstations, in order to maximize the line efficiency (Jusop & Ab Rashid, 2015), hence, the choice of the SALBP-E problem in this paper.

The scientific goal of this article is to propose a new mathematical model that balances automotive assembly lines based on minimizing the total idle time and introducing new feasibility rules and new constraints for the cycle time and other inputs.

Materials and Methods

Presentation of the existing model

(Esmaeilbeigi et al., 2015) proposed a model based on the optimization of the upper and lower bounds of the cycle time and the number of workstations. The authors of this article have chosen this model as a basic model. This model defines the SALBP-E problem as follows: “The total amount of work required to assemble the final product is divided to a group of elementary tasks. These tasks are optimally assigned to specific workstations while minimizing the cycle time and the number of workstations at the same time while respecting the given upper and lower bounds, in order to maximize the efficiency of the line". In order to establish the basic mathematical model, the following notations and assumptions are adopted by (Esmaeilbeigi et al., 2015).

Notations:

n	Number of tasks $(i = 1 \dots, n)$
m	Number of stations $(j = 1 \dots, m)$
t_i	Task time for task i
t_{max}	The maximum of the task times t_i
t_{min}	The minimum of the task times t_i
t_{tot}	Summation of task times $t_{tot} = \sum t_i$
T	Total time spent on the assembly line $T = t_{tot} + t_{dl}$
C	Cycle time
E_f	Efficiency of the assembly line
C_{max}	Cycle time upper bound
C_{min}	Cycle time lower bound
M_{max}	Number of stations upper bound
M_{min}	Number of stations lower bound
E_i	Earliest workstation of task i
L_i	Latest workstation of task i
P	the set of precedence relations $(m,k) \in P \rightarrow taskmstartsbeforetaskk$

$$X_{ij} = \begin{cases} 1, a\ task\ i\ is\ assigned\ station\ j \\ 0, \wedge\ otherwise \end{cases}$$

$$\delta_j = \begin{cases} 1, a\ task\ is\ assigned\ station\ j \\ 0, \wedge\ otherwise \end{cases}$$

The upper and lower bounds of number of workstations M_{max} and M_{min} are predefined in order to respect the design and capacity of the factory:

M_{max} and M_{min} are given and C_{max} and C_{min} are defined by (Esmaeilbeigi et al., 2015) using the following formula:

$$C_{min} = max\left\{\lceil\frac{t_{tot}}{m}\rceil, t_{max}\right\} \quad (1)$$

$$C_{max} = max\left\{2 \times \lfloor\frac{t_{tot}}{m}\rfloor, t_{max}\right\} \quad (2)$$

In order to check the validity of data, the following condition must be respected:

$$t_{max} \leq C_{max} \leq t_{tot} \quad (3)$$

Mathematical model:

$$SALBPE: minT \quad (4)$$

Subject to: $$\sum_{j=E_i}^{L_i} X_{ij} = 1 \quad (5)$$

$$\sum_{j=E_w}^{L_w} w.X_{wj} \leq \sum_{j=E_z}^{L_z} z.X_{zj} \forall (w,z) \in P \quad (6)$$

$$\delta_j \in \{0,1\} \quad (7)$$

$$X_{ij} \in \{0,1\} \quad (8)$$

$$\sum t_i.X_{ij} + t_{dlj} \leq C \quad (9)$$

$$\sum t_i.X_{ij} + t_{dlj} \leq C_{Max}.\delta_j \quad (10)$$

Constraints:

- The objective function (4) minimizes the line capacity in order to maximize the line efficiency
- Constraint (5) guarantees that a task is not assigned to more than one workstation
- Constraint (6) guarantees that the precedence relations are respected
- Constraint (7) ensures that the decision variable δ_j is binary, and it is used to indicate whether any task is assigned to station *j*
- Constraint (8) ensures that the decision variable X_{ij} is binary, and it is used to indicate whether task*i* is assigned to station *j*
- Constraints (9) and (10) impose that for any station j, the total time $\left(t_i + t_{dlj}\right)$ is lower than the line cycle time and the upper bound of the cycle time.
- The procedure is run for all possible m (number of workstations) until finding the optimal configuration and best efficiency.

Critical review of the model

The mathematical model studied in the previous section is adapted to assembly lines that do not require observance of the chronological order of the assembly operations, such as the assembly lines of textile, plastic, and other industries. On the other hand, in the automotive industry, the assembly lines must carefully respect the rules of chronological order of the execution of the tasks in order to avoid the assembly of one part before the following part in the logical assembly scheme. Moreover, the existing model does not take into account the waiting time in each workstation and assumes that the flow between workstations is a continuous flow, which is not applicable to automotive assembly lines due to the repetitive stops of the line for certain causes such as breakdowns, shortages, starvation of the lines, and other possible causes.

The existing model focuses on minimizing the total time spent on the assembly line, which requires more computational time, especially for large problems. Therefore, the authors propose a new model that takes into account precedence and feasibility constraints, and aims to maximize the efficiency of the assembly line while minimizing the number of workstations and the cycle time of the line.

FORMULATION OF THE NEW MODEL

Presentation of the proposed model:

The proposed model is based on minimizing the idle time of the line instead of the line capacity and introducing the feasibility rules and waiting time to the existing model in order to adapt it to the automotive sector. In order to establish the new mathematical model, the following notations and assumptions are adopted.

Notations:

t_{dlj} Idle time of the station j ($t_{dlj} \geq 0$

t_{dl} Idle time of the assembly line $t_{dl} = \sum t_{dlj}$

t_{wj} Waiting time of the station j ($t_{wj} \geq 0$

t_w Waiting time of the line $t_w = \sum t_{wj}$

F_{ij} Feasibility rule

$$F_{ij} = \begin{cases} 1, task\ i\ is\ feasible\ in\ station\ j \\ 0, otherwise \end{cases}$$

As seen earlier, the objective of the SALBP-E is to maximize the efficiency of the line, which can be calculated using the formula:

$$E_f = \frac{t_{tot}}{T} = \frac{t_{tot}}{t_{tot}+t_{dl}+t_w} \qquad (11)$$

t_{tot} and t_w are constant values while t_{dl} is variable; therefore, we can focus on minimizing directly the idle timet_{dl} to maximize the line efficiency.

Mathematical model:

The new proposed model is formulated as follows:

$$SALBPE: min \qquad (12)$$

Subject to: $\sum_{j=E_i}^{L_i} X_{ij} = 1$ (13)

$$\sum_{j=E_w}^{L_w} w.X_{wj} \leq \sum_{j=E_z}^{L_z} z.X_{zj} \forall (w,z) \in P \qquad (14)$$

$$\delta_j \in \{0,1\} \qquad (15)$$

$$X_{ij} \in \{0,1\} \qquad (16)$$

$$F_{ij} \in \{0,1\} \qquad (17)$$

$$X_{ij} = \begin{cases} 0, \wedge F_{ij} = 0 \\ 1, \wedge F_{ij} = 1 \end{cases} \qquad (18)$$

$$C_{min} \leq C \leq C_{max} \qquad (19)$$

$$\sum t_i.X_{ij} + t_{dlj} \leq C \qquad (20)$$

$$\sum t_i.X_{ij} + t_{dlj} \leq C_{Max}.\delta_j \qquad (21)$$

Constraints:

- The objective function (12) minimizes the idle time of all the stations of the assembly line, which maximizes the line efficiency as seen earlier in equation (4).
- (13) guarantees that each task is assigned to one and only one workstation.
- Constraint (14) ensures respecting the precedence relations.
- Constraint (15) ensures that the decision variable δ_j is binary, and it is used to indicates whether any task is assigned to the station j.
- Constraint (16) ensures that the decision variable X_{ij} is binary.
- Constraint (17) ensures that the feasibility variable is binary, while constraint (18) guarantees that only feasible tasks are assigned to each workstation.
- Constraint (19) imposes the lower and upper bounds of the cycle time.
- Constraints (20) and (21) imposes that for any station j, the total time $\left(t_i + t_{dlj}\right)$ is lower than the line cycle time.
- The algorithm is run for all possible m (number of workstations), until finding the optimal configuration and best efficiency.

CASE STUDY

In most cases in the automotive industry, the vehicle starts from the stamping section, goes to the metallurgy section, to the painting section, and finally enters the assembly section, where our study is conducted. The assembly plant is generally composed of 2 workshops: the mechanical workshop, where the assigned workers assemble the basic mechanical parts of the vehicle, such us the engine, the radiator, and the transmission, and the interior assembly workshop, where the operators assemble all the interior pieces. Each workshop is composed of many elementary lines. Our study is conducted in the seating system assembly line, also called “ME6 line”, where the operators assemble the seating system (S. E. A. El Ahmadi & El Abbadi, 2022).

Table 2 and figure 2 show the assembly sequence of the seating system in a typical car, referred to as X52. First, the parts are transferred from the centralized inventory to the buffer stocks between each two workstations, then the assembly operations of the parts are launched (seat truck, seat base, seat belt, seat cover, backrest, armrest, headrest, and central box).

Table 2. Assembly sequence of the automotive seating system

N°	Operation	Part to assemble	Part to assemble on	Time
1	Fix the seat truck on the car floor	Seat Truck	Car floor	17 s
2	Fix the seat base on the Seat truck	Seat base	Seat truck	13 s
3	Fix the backrest on the seat truck	Backrest	Seat truck	16 s
4	Fix the armrest on the central box	Armrest	Central box	16 s
5	Fix the central box on the car floor	Central box	Car floor	18 s
6	Fix the seat belt on the seat base and the central box	Seat belt	Seat base, Central box	20 s
7	Fix the headrest on the Backrest	Headrest	Backrest	15 s
8	Fix the seat cover on the seat	Seat cover	Seat	17 s

The bounds of the number of workstations are given by the process engineers of the factory due to factory design and surface restrictions, such as $M_{min} = 3$ and $M_{max} = 5$. Based on the task times shown in Table 2 and equations (1) and (2), C_{min} is computed as 33s and C_{max} is computed as 66s, which means that according to condition (12):

$$33s \leq C \leq 66s \qquad (22)$$

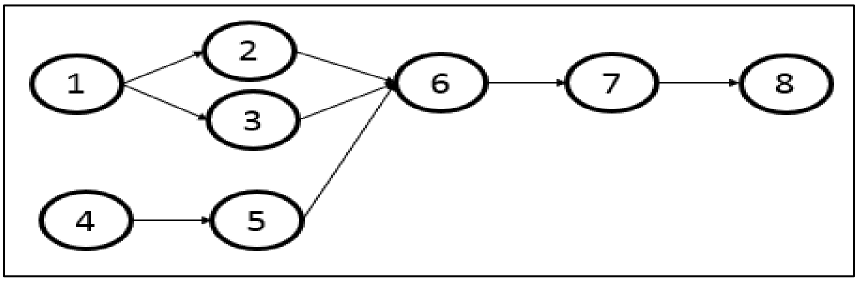

Fig. 2. Precedence graph of the studied line ME6

Based on the precedence graph (figure 2), the precedence matrix is given as:

$$\begin{pmatrix} 0 & 1 & 1 & 00 & 0 & 0 & 0 \\ 0 & 0 & 0 & 00 & 1 & 0 & 0 \\ 0 & 0 & 0 & 00 & 1 & 0 & 0 \\ 0 & 0 & 0 & 01 & 0 & 0 & 0 \\ 0 & 0 & 0 & 00 & 1 & 0 & 0 \\ 0 & 0 & 0 & 00 & 0 & 1 & 0 \\ 0 & 0 & 0 & 00 & 0 & 0 & 1 \\ 0 & 0 & 0 & 00 & 0 & 0 & 0 \end{pmatrix}$$

RESULTS

Feasibility rules F_{ij} of each task are given by the process engineers according to technical conditions of workstations and the availability of the requirements of each task in each workstation, and these rules are formulated as shown in tables 3, 4, and 5:

Table 3. Feasibility rules for $m = 3$

Task	Feasibility Workstations
1	1, 2, 3
2	1, 3
3	2, 3
4	1, 3
5	1, 2, 3
6	1, 2, 3
7	1, 2
8	3

Table 4. Feasibility rules for $m = 4$

Task	Feasibility Workstations
1	1, 2, 3, 4
2	1, 3
3	2, 3
4	1, 3, 4
5	1, 2, 3
6	1, 2, 3
7	1, 2, 4
8	4

The algorithm is run for all possible number of workstations (3, 4, and 5), and in our case, the optimal number of workstations obtained for the studied assembly line is $m = 4$. Then the test is done for 4 workstations for all possible cycle times between the upper and lower bounds in order to find the minimum idle times as demanded in the objective function (5).

Table 5. Feasibility rules for $m = 5$

Task	Feasibility Workstations
1	1, 2, 3
2	1, 3
3	2, 3
4	1, 3, 5
5	1, 2, 3, 4
6	1, 2, 3, 4
7	1, 2, 4, 5
8	5

Based on the test done and (22), the best line efficiency obtained is $E_f = 96{,}35\%$ for an optimum cycle time $C = 34s$ with the following assignment matrix:

$$\begin{pmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

The assignment of tasks to workstations is the following:

- Tasks 4 and 5 assigned to workstation 1, with a workstation time $T_{WS1} = 34s$, which is the cycle time of the line $C = 34s$ (the higher workstation time).
- Tasks 1 and 3 assigned to workstation 2, with a workstation time $T_{WS2} = 33s$.
- Tasks 2 and 6 assigned to workstation 3, with a workstation time $T_{WS3} = 33s$.
- Tasks 7 and 8 assigned to workstation 4, with a workstation time $T_{WS4} = 32s$.

Four workstations are identified by using the model, as shown in figure 3, with respect of the precedence and feasibility rules and a new cycle time of 34 seconds.

Before the implementation of the algorithm, the studied assembly line was composed of 3 workstations with a cycle time $T_c = 52s$ and the workstation times vector $T_{WS} = (46{,}34{,}52)$, which guarantees an efficiency $E_f = 84{,}615\%$.

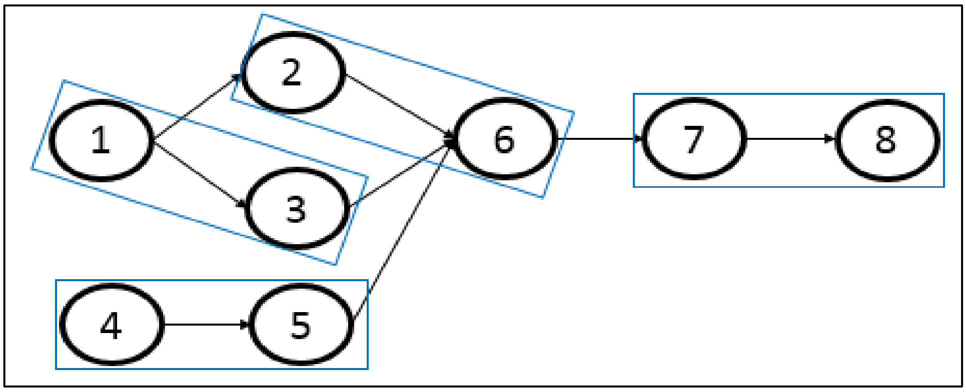

Fig. 3. Studied line ME6 after the balancing

DISCUSSION

The use of the new algorithm improved the efficiency of the line to $E_f = 97{,}059\%$ for four workstations, with workstation times vector $T_{WS} = (34{,}33{,}33{,}32)$ and a new cycle time $T_c = 34s$, which means an improvement of 14% in the total line efficiency and a reduction of 18s in the cycle time. These results are presented in Table 6:

Table 6. Comparison of the results before and after using the proposed algorithm

	Before	After
Number of workstations	3	4
Cycle Time	52 s	34 s
Total time of the line	156 s	136 s
Idle time of the line	24 s	4 s
Efficiency	84,615%	97,059%

A comparison study is made between the results obtained based on our model and the results obtained based on other existing models in the literature. (Esmaeilbeigi et al., 2015) proposed general cutting planes and precedence-oriented valid inequalities to solve the problem and included appropriate auxiliary variables to reduce the solution time. The proposed model by (Wei & Chao, 2011) minimizes the total idle time to optimize the assembly line balancing efficiency while using two variables Ei and Li. (Zacharia & Nearchou, 2013) studied the fuzzy extension of the general version of the SALBP-E problem and considered the problem of finding a feasible balance assignment of the tasks to the stations such that both the number of the stations and the fuzzy cycle time of the line is minimized.

The results obtained from the proposed mathematical models are presented in Table 7.

Table 7. Comparison of the efficiency of the proposed model with other models from the literature

Mathematical model	Efficiency
Model proposed in this article	97,059%
(Esmaeilbeigi et al., 2015)	84,615%
(Wei & Chao, 2011)	82,231%
(Zacharia & Nearchou, 2013)	80,112%

CONCLUSION

The present research work proposed a new model for solving the SALBP type E problem in the automotive industry, in which the objective is to augment the efficiency by minimizing the number of workstations and cycle time simultaneously. The model takes into account precedence and feasibility rules and the optimization of other constraints.

LIMITATIONS OF RESEARCH

The presented model is not free from some limitations. The model will be difficult to exploit in large-scale optimization problems because of the large number of constraints presented. Moreover, although the model proposed in this paper can be generalized, it requires more improvements and adaptation efforts for multi-model or mixed assembly lines in order to obtain the optimal efficiency of the line in an optimal computation time. Future work could be to develop this proposed SALBP-E model for multi model or mixed model assembly lines.

for multi model or mixed model assembly

lines.

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