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Reducing Flow Time in an Automotive Asynchronous Assembly Line – An application from an automotive factory

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Abstract

The automotive industry is a highly competitive sector. Manufacturers must effectively control highly complex production processes in order to fulfil all customer orders for customized cars on time, on budget and to the required quality.

In this paper, the authors focus on improving the flow time of asynchronous automotive assembly lines by reducing the buffer time. A simulation-search heuristic procedure was developed and confirmed in a 5 workstations asynchronous assembly line installed in an automotive company.

The proposed procedure identifies optimal performing buffer profiles for each storage level which guarantees lowest flow time while keeping the same throughput level.

Experiments results show that our new algorithm significantly outperforms existing results, especially for large scale problems.

Keywords

Automotive industry, flow time, asynchronous assembly line, buffer time, buffer profiles.

Introduction

During the last decade, most of the manufacturing units have shown a deep concern to improve their business standards in order to remain in the competitive marketplace and to maintain good productivity levels (Hussain & Jan, 2019; Meidan et al., 2017) based on reliability impression which is the primary aspect of the automatic assembly line for continuous production (Hussain, 2019a). An assembly line is defined as a flow-oriented production system used in mass production industries especially in the automotive industry (El Ahmadi et al., 2019), and it consists of many manual or automated workstations organized to perform a group of assembly tasks necessary to produce a final product which is generally a car or part of a car (wheel, seat, engine ...) in automotive assembly lines. The first workstation of the assembly line is generally fed by a manufacturing system, after the processing time, the product is transferred to the next workstation, each task has a processing time and each workstation has its assigned tasks, and the total assembly process duration is in general uncertain (El Ahmadi & El Abbadi, 2020b; Hussain, 2019b).

In the literature, researchers have proposed many possible classifications of assembly lines based on several criteria such as workflow characteristics, product characteristics, layout characteristics, task time characteristics, assumption characteristics and objectives of the problem (Saif et al., 2014)

In a previous work, the classification of assembly lines according to workflow characteristics was developed and an overall comparison was made between three types of automotive assembly lines: paced, unpaced synchronous and unpaced asynchronous lines, and as a result of this comparison the authors found that the asynchronous assembly line outperforms the other lines in the productivity, Quality and ergonomics factors, but to be improved in terms of flow time (El Ahmadi & El Abbadi, 2020a).

The topic of improving the flow time of an assembly line is already studied in the literature especially by reducing the buffer time, but the proposed methods are very slow in reducing the flow time, especially in large scale problems, This paper proposes a new simulation-search heuristic procedure that reduce the flow time of an assembly line based on studying each workstation with its previous and next buffer and comparing its cycle time with the takt time of the assembly line to decide to activate or deactivate the

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buffer. A case study is conducted using the proposed procedure to reduce the flow time of an automotive unpaced asynchronous assembly line composed of 5 workstations (WS_1, WS_2, WS_3, WS_4, WS_5) and 4 interstation buffers (B_1, B_2, B_3, B_4).

Background of study

In asynchronous assembly lines, the flow of products isn't coordinated unlike in synchronous lines, the operator starts performing his tasks and pass to the next work piece after finishing without waiting for the end of the cycle time and without waiting the next or previous operator to finish his tasks. In order to minimize the waiting times caused by variations between cycle times of workstations, buffer stocks are used between stations, which can compensate for the deviations in task times (El Ahmadi & El Abbadi, 2020a; Boysen et al., 2007; Mantin & Veldman, 2019).

Buffer storage is defined as the number of storage spaces for products between two different stages of the process throughout the line (Ameen et al., 2018), and the problem dealing with the configuration of buffers is known in the literature as the buffer allocation problem (BAP) and it is an NP-hard combinatorial optimization problem in the design of production lines (Demir et al., 2012).

Therefore, the difference between the workload of two workstations W_j and W_{j+1} decides if there will be blockage of starvation between them.

If $W_j < W_{j+1}$ then after completing the processing of the work pieces on station W_j, they will move to the buffer $B_{j,j+1}$ instead of moving directly to the station W_{j+1}. However, it depends also on the buffer size to decide whether there would be starvation or blockage. The station W_j may not be blocked if the following condition remains true (El Ahmadi & El Abbadi, 2020b):

$$P_j \times (W_{j+1} - W_j) < B_{j,j+1} \tag{1}$$

where:
P_j – the production rate of station j,
$B_{j,j+1}$ – the buffer between W_j and W_{j+1},
W_j – the workload of the station j.

Also, if $W_j > W_{j+1}$ then after completing all the tasks on station W_j, the work pieces will move to the next buffer $B_{j,j+1}$. It depends also on the buffer size between the two stations W_j and W_{j+1} which will decide the starvation of the station W_{j+1}. The station W_{j+1} will not starve if the following condition remains true (El Ahmadi & El Abbadi, 2020a):

$$P_{j+1} \times (W_j - W_{j+1}) < B_{j,j+1} - S_{j+1} \tag{2}$$

where: S_{j+1} – the existing stored parts in the buffer for processing on station W_{j+1}.

Researchers have confirmed that the high net cost of production is the result of the high flow time which means that work pieces remain too long in the production process (Królczyk et al., 2015), therefore the authors will focus in this paper on minimizing the flow time of asynchronous assembly lines while avoiding the blockage and starvation of the workstations and keeping the same production output level.

Flow time (also called the throughput time) is the time that elapses as the assembly line performs all the operations necessary to complete a work order, this flow time has many components, including the processing time, buffer time, control time and transportation time (Królczyk et al., 2015)

$$F_t = B_t + C_t + T_t + P_t \tag{3}$$

where:
F_t – flow time,
B_t – buffer time,
C_t – control time,
T_t – transportation time,
P_t – processing time.

Since the important use of asynchronous assembly lines in the manufacturing companies, a large number of research studies have been conducted to study their behavior and to determine ways of improving their performance and their flow time.

Buffer time

Reducing the buffer time is a topic of interest of many researchers, Alfieri et al. (2020) developed a new row-column generation algorithm for the buffer allocation problem BAP in assembly and disassembly systems. Demir & Koyuncuoğlu (2021) developed a variable neighborhood search algorithm to solve the Buffer allocation problem with the objectives of throughput maximization and total buffer size minimization. Shao et al. (2020) combined two well-known evolutionary algorithms to solve the buffer allocation problem in automotive production systems: the non-dominated sorting genetic algorithm (NSGA-II) and the multi objective particle swarm optimization (MOPSO). Qudeiri et al. (2007) proposed a production simulator (PS) to determine optimal or near optimal buffer size and it consists of a genetic algorithm and a discrete event. Demir & Tunali (2008) presented a new solution to the optimal allocation of buffers in that combines subgradient algorithm proposed by Gasimov & Ustun (2007) and genetic algorithms within the same framework to maximize the throughput of the production line. Qudeiri et al. (2008) attempted to find the nearest optimal design of a S-PPL that will maximize production efficiency by optimizing the following three decision variables: buffer size between each pair of work stations, machine numbers in each of the work stations, and machine types using a new genetic algorithm simulation-based method. Yamamoto et al. (2008) presented a new production simulator system (PSS) which consists of a genetic algorithm system and a discrete simulator to decide a buffer size for any flexible transfer line with bypass lines. Kose (2010) suggested a new hybrid method which combines a genetic algorithm and simulation to allocate buffers in an optimal way.

Control time

Many studies are dealing with the optimization of the control time, Gharbi et al. (2022) developed an optimal control policy for unreliable manufacturing systems evolving in a stochastic and dynamic environment based on a new stochastic dynamic programming model. Cogoni et al. (2021) proposed a novel hybrid method for optimizing the quality control time in manufacturing systems by combining the online NIR PLS and sensors, enabling a robust prediction. Pacana et al. (2021) studied the improvement of the production process and the optimization of control time through the use of checkpoints and proposed a new method of quality control check in complex industrial manufacturing systems.

Transportation time

The internal transport plays a growing role in the integrated logistics management of semi-finished products and components flow. For manufacturing companies, it is important to maximize the use of production resources and optimize the process in terms of both production costs and time, many researchers proposed optimization solutions in this topic; Karimi et al. (2017) formulated the problem by two mixed integer linear programming models and proposed a novel imperialist competitive algorithm hybridized by a simulated annealing, while Liu et al. (2008) conducted their research based on two algorithms "the classical Dijsktra algorithm" and "the bidirectional Dijsktra algorithm", and proposed a new improved algorithm that reduces the search area and the time complexity. Ploydanai & Mungwattana (2010) developed a new algorithm based on a non-delay scheduling heuristic by adding machine availability constraint to solve job shop scheduling problem with minimize makespan objective. Reinhard (2014) proposed in his thesis a general model (the Complex Job Shop (CJS) model) that includes a variety of features from practice, and developed a local search heuristic characterized by a job insertion-based neighborhood and named JIBLS (Job Insertion Based Local Search).

Processing time

To reduce processing time in a manufacturing process, researchers worked on the assembly line balancing problem, to reach the optimum design of the line with the minimum possible cycle times, Wu et al. (2019) proposed a modified Monte-Carlo tree search (MCTS) algorithm to solve two-sided assembly line balancing problem (TALBP). Tang et al. (2022) improved the existing assembly line balancing algorithms and proposed a new multi-objective multifactorial algorithm that aims to minimize cycle times. Zhang et al. (2020) formulated a new mathematical model of the robotic assembly line balancing problem and presented a new hybrid multi-objective dragonfly algorithm. Andreu-Casas et al. (2021) studied the multi manned assembly line balancing problems and proposed two procedures based on solving the partition problem with constraints. Walter et al. (2021) developed a tailored branch and bound procedure aiming to smoothen workloads and reduce the processing times in the assembly line.

Case study

Introduction

The flow time is the summation of four components as seen in formula (3), therefore flow time improvement can be achieved either by reducing buffer time (optimal design and allocation of buffers and inter-stations inventory), reducing transport time (internal transport time or optimal physical flow design), reducing control time (time required to inspect and verify defects in the part) or optimizing processing time (using assembly line balancing methods).

This study is conducted based on a real case in an automotive company that produces 1200 car per day, to choose the right component to reduce in order to improve the flow time in an optimal way.

Studied line

In the automotive industry, in most cases the vehicle passes by the stamp department, body department, painting department and finally the assembly department where our study took place. The studied line is called the preparation line (referred to as PR1) and it consists on workers preparing the dashboard before sending it to the main assembly line, and it is composed of 5 workstations and note that the takt time $T_k = 2$ minutes.

The first step of the studied process is the connection between the dashboard and the engine in WS_1, the second step is the connection of the dashboard with the screen washer level using two cables in WS_2, the fuel level detector is connected in WS_3, finally the air-conditionning system and the stereo system are installed in WS_4 and WS_5 as shown in Figure 1.

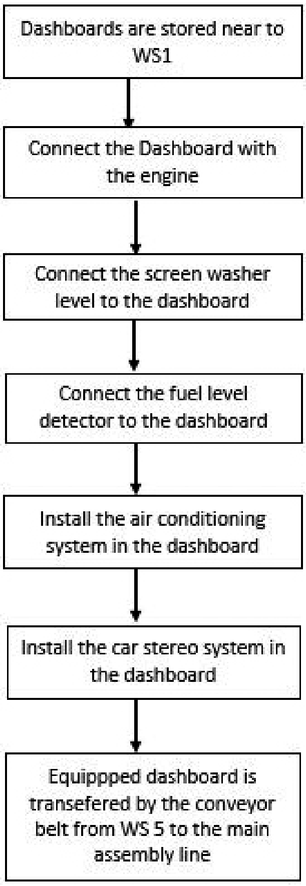

Fig. 1. Process flow diagram

Figure 2 shows the workstations (circles) and the buffers (inverted triangles), the numbers inside the circles are the cycle times, and the numbers inside the inverted triangles mean the number of parts stored in the buffer.

The processing time is calculated as the sum of the cycle times of the five workstations, the transportation time is measured by the timing of the transfer of the dashboard between workstations and between the WS_5 and the main assembly line, the control time is also measured by the timing of control operations in the five workstations, while the buffer time is calculated using the formula (4):

$$B_t = \sum P_j \times B_{j,j+1} - P_t \tag{4}$$

P_j – the production rate of station j,
$B_{j,j+1}$ – the buffer between W_j and W_{j+1},

The following results are obtained for the studied line:

- $P_t = 13$ minutes
- $T_t = 1.2$ minutes
- $C_t = 2$ minutes
- $B_t = 47$ minutes

Analysis of data

The flow time of the studied line is the summation of the four components as shown in formula (3), which is $F_t = 63.2$ minutes in our case, and it is divided as shown in the graph Fig. 3; the buffer time B_t is the more significant component in the flow time (74%) so the authors will focus on this paper on optimizing the buffer time, the problem is known in the literature as the Buffer allocation problem (BAP), and it deals with finding optimal buffer sizes to be allocated into

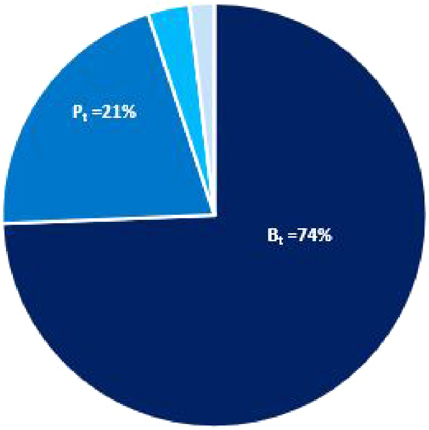

Fig. 3. Flow time distribution

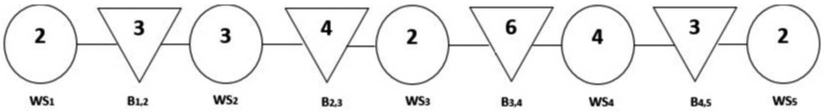

Fig. 2. The studied line (PR1)

buffer areas in a production line to achieve a specific objective, and the following objective functions are the main in the literature:

- Objective 1: Throughput maximization;
- Objective 2: Total buffer size/work in Process (WIP) minimization;
- Objective 3: Cost minimization;
- Objective 4: Profit maximization;
- Objective 5: Other objective functions, such as maximizing customer service level, minimizing the mean waiting time of a job, reducing idle time, minimizing cycle time.

In this paper, authors are searching to minimize the buffer time and to find the optimal buffer allocation (OBA) that minimizes the average work-in-process (WIP) inventory while keeping the same production output (objective 2).

In the following Table 1 the authors present all the possible buffer profiles in the studied line for a storage capacity $S = 2$, which is predefined in order to respect the storage constraints:

Table 1
All possible buffer profiles in the studied line for $S = 2$

Combination	Buffer				Capacity of storage of the line "S"
	BF1	*BF2*	*BF3*	*BF4*	
1	1	0	0	0	1
2	0	1	0	0	
3	0	0	1	0	
4	0	0	0	1	
5	1	1	0	0	2
6	1	0	1	0	
7	1	0	0	1	
8	0	1	1	0	
9	0	1	0	1	
10	0	0	1	1	
11	2	0	0	0	
12	0	2	0	0	
13	0	0	2	0	
14	0	0	0	2	

Note that the number of different ways of allocating S spaces to n buffers can be determined using the following formula (5):

$$\binom{S+(n-1)}{S} = \frac{(S+n+1)!}{S!(n+1)!} \tag{5}$$

In the studied line, 4 buffers are allocated ($n = 4$), and the capacity of storage is variable ($S \geq 0$); the number of possible solutions is regrouped in the following Table 2:

Table 2
Number of possible buffer profiles

n	S	Number of buffer profiles
4	1	4
4	2	10
4	3	20
4	4	35
4	5	56
4	6	84
4	7	120
4	8	165
4	9	220
4	10	286

For each specific total storage level, all buffer profiles must be examined to determine which one provides the lowest flow time and the same level of production output, but the authors can see that as the number of storage space increases for a fixed number of buffers, the number of buffer profiles increases arithmetically. Furthermore, as both of the number of buffers and the number of total storage spaces increase, the complexity of the problem increases rapidly, so our goal is to minimize the complexity of the problem.

If a simulation is run for each of the buffer profiles with a total storage of 2 units, then one or more of the profiles will result in a minimum flow time with the maximum level of output. The resulting output level however may not be the global maximum output level of the line. If the simulation is rerun with a total storage of 4 units, then the highest output level may exceed that when the total storage was 3 units but the increased logistics costs and inventory constraints must be taken into consideration.

Proposed algorithm

Presentation of the algorithm

Assume that there is a $n+1$ workstations assembly line $(WS_1, \ldots, WS_n)$ with $B_a = (B_1, \ldots, B_n)$ the actual buffer vector, $B_{i,i+1}$ Boolean $B_{i,i+1} = (0, 1)$ with $(i = 1, 2, \ldots, n)$, T_i cycle time of workstation WS_i and T_K the takt time of the assembly line. The goal of the algorithm is to find the optimal buffer allocation (OBA) that guarantees the minimum buffer time and the same production output (PO) of the current buffer.

In mathematical terms the problem (P) could be stated as follows:

$$(\mathrm{P})\colon \text{Find } B^* = \left(B_1^* B_2^*, \ldots, B_n^*\right) \quad \text{to } \min\left(WIP\left(B^*\right)\right) \tag{6}$$

with:

$$\sum_{i=1}^{n} B_i^* = S \tag{7}$$

$$PO\left(B^*\right) = PO(B_a) \tag{8}$$

First step:

The buffer between the workstation w_i and w_{i+1} is off (not used), if the worker i is slower than the worker $i+1$, in this case the assembly line balancing is necessary:

For $i \in (1, \ldots, n)$

$$\text{if } \ (T_i \geq T_{i+1}) \tag{9}$$

$$\text{then } \ (B_{i,i+1} = 0) \tag{10}$$

Repeat the first step to all the workstations.

Second step:

In the other side, if the worker i is faster than the worker $i+1$ and faster than the pace of the line (takt time) at the same time, then the authors use the OPT technique to compensate the difference of cycle times:

$$\text{if } \ T_i \leq T_k) \tag{11}$$

$$\text{then } \ (T_i = T_k) \tag{12}$$

Third step:

If (9) and (11) are not correct, then the worker i is faster than the worker $i+1$ and slower than the line pace, then in this case the buffer $B_{i,i+1}$ is activated

$$\text{if } \ (T_k \leq T_i \leq T_{i+1}) \tag{13}$$

$$\text{then } \ (B_{i,i+1} = 1) \tag{14}$$

Fourth step:

All buffers $B_{i,i+1}$ are assigned as in (15), either $B_{i,i+1} = 0$ which means that the correspondent buffer will not be used ($B_i^* = 0$) or $B_{i,i+1} = 1$ which means that the correspondent buffer is used and will be an integer number between 1 and the capacity of the storage of the line S:

$$B = (B_{1,2} B_{2,3}, \ldots, B_{i,i+1}) \tag{15}$$

$$\text{if } \ (B_{i,i+1} = 1) \ \text{ then } \ (B^*_{i,i+1} \in [1, S]) \tag{16}$$

$$\text{else if } \ (B_{i,i+1} = 0) \ \text{ then } \ (B^*_{i,i+1} = 0) \tag{17}$$

Run the buffer allocation search table and find (B^*).

Discussion of results

Consider that the algorithm is run on the studied line to compare the results before and after, the authors rerun the buffer profiles search and collect data in the following Table 3:

Table 3
Possible buffer profiles for $S = 2$ after using the algorithm

Combination	Buffer				Capacity of storage of the line
	BF1	*BF2*	*BF3*	*BF4*	
1	1	0	0	0	1
2	0	0	1	0	
3	1	0	1	0	2
4	2	0	0	0	
5	0	0	2	0	

Two buffers were turned off after using the algorithm, because the condition (9) is verified, $B_{2,3} = 0$ and $B_{4,5} = 0$, the condition (13) isn't verified for the two other buffers because the takt time of the line is 2 minutes, but this condition could be verified if the takt time was more than 3 minutes, so the algorithm moves directly to the third step and confirmed that the $B_{1,2} = 1$ and $B_{3,4} = 1$ therefore the Boolean buffer vector is $B = (1, 0, 1, 0)$ As a result, for a storage capacity $S = [1, 2]$ the authors get 5 possible buffer profiles (2 profiles for $S = 1$ and 3 profiles for $S = 2$) instead of 14 buffer profiles that the authors found in the first experiment.

The authors present in the following graph (Figure 4) the evolution of the number of possible buffer profiles for every capacity of storage before and after using the algorithm:

As can be seen in Figure 4, the increase in the storage capacity of the line significantly influences the number of possible buffer profiles, it can be observed in Table 2 that for a storage capacity storage of 10 pieces, the buffer allocation search table must verify 1000 possible buffer profiles and test each one of them to find the buffer profile that guarantee the maximum level of production output and the minimum buffer time. After using the algorithm, the number of buffer profiles for each capacity of storage decreases

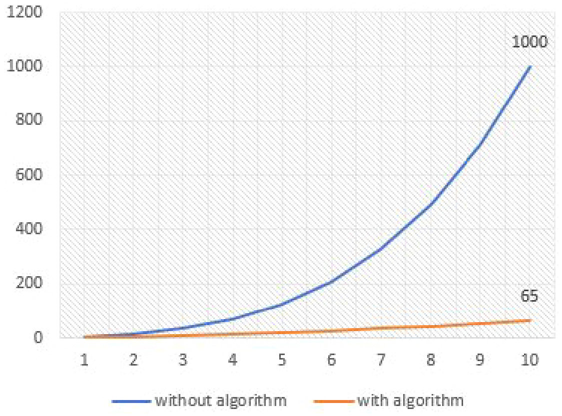

Fig. 4. Number of possible buffer profiles before/after the use of algorithm

significantly because many buffers could be turned off and the differences between cycle times and the takt time are compensated, in our studied line 50% of the buffers were turned off and the calculation became easier; for a storage capacity of 10 pieces, the number of possible buffer profiles decreased from 1000 to 65 which is much easier to manage.

Conclusions

In the present work, the problem of reducing flow time in an automotive asynchronous assembly line was studied. The developed mathematical model is based on considering a buffer off if $T_i \geq T_{i+1}$ and comparing the cycle time of each workstation with the takt time of the line using the OPT technique, and it was evaluated on a set of instances from a case study in an automotive company. The obtained results were promising and have shown its applicability. All possible instances were solved in an optimal way.

For further research, a new direction to investigate is to adapt this algorithm in case of all workstations are already organized following cycle time in a descending order so more work can be done to generalize and improve the proposed algorithm in this case.

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