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An integrated model for cost-oriented assembly line balancing and parts feeding with supermarkets

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Abstract

This paper aims to deal with assembly line design from both line balancing and parts feeding (PF) aspects as two-interrelated decision problems while supermarkets are used. These problems arise in the real-world assembly lines (ALs) where decision makers are planning to simultaneously determine the optimal number of stations and the optimal number of supermarkets so that the total installation costs of ALs including line balancing and PF costs are minimized. To this purpose an integrated mathematical model is proposed and its performance is tested through solving a number of benchmark problems and a real case taken from industry.

Keywords: assembly line balancing; parts feeding, supermarket, mathematical model; cost optimization

1. Introduction

Nowadays in lean manufacturing systems the productivity of assembly lines (ALs) is highly dependent upon the number of stations and the in-house logistics needed for their parts supply. The number of stations in the ALs is primarily dependent on the assignment of the assembly tasks to the stations which has been widely known as assembly line balancing (ALB) problem [1].

Moreover, unlike the past feeding policies, where parts have to be delivered from a central warehouse, recently, supermarkets are used to feed parts to the stations as decentralized storage areas near the ALs to enable a flexible and reliable part supply of stations [2]. However, since the space on the shop floor is scarce and valuable, the assignment of stations to the supermarkets so that the optimal number of supermarkets are determined has been recently defined as the long-term decision problem in parts feeding (PF) using supermarkets [3].

The ALB and determining the optimal number of supermarkets are interdependent decision problems. Through ALB the assembly tasks are assigned to the stations so that the number of stations are optimized while stations times do not exceed a given cycle time (*CT*). On the other hand, to determine the optimal number of supermarkets the assignment of stations (including their involving tasks and part requirements) to the supermarkets has to be addressed while the capacity of the supermarkets is not exceeded.

Although ALB and supermarket location problems have been separately addressed however, it was proved that these problems are interrelated [4]. Moreover, according to the authors' best knowledge a very few studies have simultaneously addressed ALB and determining the optimal assignment of stations to supermarkets and accordingly obtaining the optimal number of supermarkets. Therefore, this study aims to propose a new integrated mathematical model in which both problems are jointly addressed within a single step. The proposed model is applied on a real case and a set of benchmarks taken from ALB literature.

The reminder of this paper is organized as follows. Section 2 reviews the relating literature. Section 3 presents the problem formulation. Section 4 presents the computational results, and

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finally the conclusions and future research directions are provided in Section 5.

2. Literature review

Although the ALB and PF problems have been separately studied in their relating literatures [5,6], however, to the best of the authors' knowledge very few studies have been performed in the literature where both ALB and PF using supermarkets are jointly dealt with [4]. Sternatz [7] analyzed the interdependence of the line balancing and material supply problems and revealed the potential gains through simultaneous planning. They proposed a joint ALB and PF in which the direct and indirect supply policies from central warehouses and other real world constraints such as the space capacity of the stations were considered. Battini et al. [8] discussed the potential reduction of the labor's ergonomic pressures through the integrated planning of ALB and PF. They proposed an integrated model and applied it on self-priming pump AL in which the ergonomics risk of the operators is optimized while ALB and PF problems are simultaneously addressed. Nourmohammadi and Eskandari [4] proposed a two stage mathematical programming model to deal with both ALB and SLP. However, they sequentially addressed these problems where the results of the ALB model were fed to SLP model to find the optimal number of supermarkets. Battini et al. [9] provided a step-by-step procedure to support materials management by determining the level of centralization/decentralization while minimizing the supermarkets' inventory and transportation costs. In [10], an efficient genetic algorithm was proposed to address the SLP while the unavailability of some places for supermarkets as well as the capacity limitation of the supermarkets in terms of the bin number were considered.

Reviewing the literature reveals that there is no study, simultaneously dealing with both ALB and PF using supermarkets in an integrated approach. Therefore, this study aims to propose a new mathematical model in which both problems are jointly addressed.

3. Problem description

From ALB aspect we consider a single straight AL in which there are a number of tasks ($i = 1, \dots, n$), each with a given precedence relationships represented by a set of ordered pairs of tasks. The task time (t_i) and the task demands (d_i) in bins are known in advance as shown by the upper and lower weights for each task, respectively in Fig. 1. The tasks are assigned to stations $k = 1,\dots,K$ according to their precedence relationships

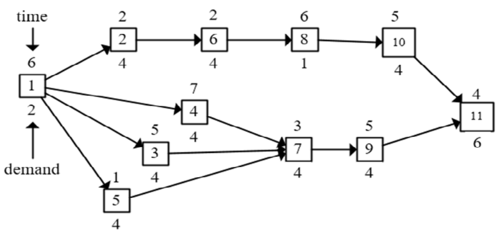

Fig. 1. The precedence graph for the 11-task ALBP

so that number of stations is minimized while ensuring that the station times do not exceed the given CT [11].

From PF using supermarket aspect, we aim to feed stations $k = 1,\dots,K$ each requiring ds_k bins of parts to be supplied from supermarkets $s = 1,\dots,S$ ($S =$ maximum number of supermarkets). In this regard, we aim to define the optimal number of supermarkets and the stations that each should support.

Considering the above ALB and part supply problems which has been arised in a real case at a car part producer company, this study aims to determine the optimal number of stations and supermarkets from ALB and PF aspects, respectively. To this purpose an integrated model is proposed in which the assignment of tasks to stations and stations to supermarkets are defined so that the resulting number of stations and supermarkets are simultaneously minimized while ensuring that the sum of task times assigned to each station and the sum of station demands assigned to each supermarket do not exceed the given CT and supermarket capacity, respectively. It is assumed that the visit sequence of stations from each supermarket is consecutive i.e. it is not allowed to serve stations 1, 2 and 5 from the first supermarket while stations 3 and 4 receive their parts from another supermarket [10]. Parts are sorted and delivered in bins which are all identical in term of dimension [9]. The notations shown in Table 1 are used for modeling purpose.

Table 1. List of notations

Notation	Definition
i,j:	Tasks index ($i,j=1,\dots,N$)
k,l:	Stations index ($k,l = 1,\dots,K$)
s:	Supermarket index ($s = 1,\dots,S$)
CT:	The given cycle time
N:	Number of tasks
K:	Maximum number of stations
S:	Maximum number of supermarkets
t_i:	Time of task i
d_i:	Demand of task i
p_{ij}:	$\begin{cases} 1; & \text{if task } i \text{ precedes task } j \\ 0; & otherwise \end{cases}$
TC:	Total cost of balancing and PF
α:	Installation cost of one station
β:	Installation cost of one supermarket
Cap_s:	Capacity of supermarket s (number of bins)
M:	Optimized number of stations
NS:	Optimized number of supermarkets
x_{ik}:	$\begin{cases} 1; & \text{if task } i \text{ is assigned to station } k \\ 0; & otherwise \end{cases}$
y_{ks}:	$\begin{cases} 1; & \text{if station } k \text{ is assigned to supermarket } s \\ 0; & otherwise \end{cases}$
U_k:	$\begin{cases} 1; & \text{if station } k \text{ is established} \\ 0; & otherwise \end{cases}$
Z_s:	$\begin{cases} 1; & \text{if supermarket } s \text{ is established} \\ 0; & otherwise \end{cases}$
v_{iks}:	An auxiliary variable

The following model is proposed for the integrated planning of ALB and PF problems discussed above:

$$Min\ TC = \alpha \times M + \beta \times NS \tag{1}$$

$$\sum_{k=1}^{K} x_{ik} = 1 \quad \forall i = 1,\dots,N \tag{2}$$

$$\sum_{s=1}^{S} y_{ks} = 1 \quad \forall k = 1,\dots,K \tag{3}$$

$$\sum_{k=1}^{K} U_k = M \tag{4}$$

$$\sum_{s=1}^{S} Z_s = NS \tag{5}$$

$$U_k \geq x_{ik} \qquad \forall i = 1,...,N; \forall k = 1,...,K \tag{6}$$

$$Z_s \geq y_{ks} \qquad \forall k = 1,...,K; \forall s = 1,...,S \tag{7}$$

$$\sum_{i=1}^{N} t_i \times x_{ik} \leq CT \qquad \forall k = 1,...,K \tag{8}$$

$$\sum_{k=1}^{K} \sum_{i=1}^{N} d_i \times v_{iks} \leq Cap_s \qquad \forall s = 1,...,S \tag{9}$$

$$x_{ik} + y_{ks} - v_{iks} \leq 1 \quad \forall i = 1,...,N; \forall k = 1,...,K; \forall s = 1,...,S \tag{10}$$

$$x_{ik} + y_{ks} - 2v_{iks} \geq 0 \quad \forall i = 1,...,N; \forall k = 1,...,K; \forall s = 1,...,S \tag{11}$$

$$\sum_{f=1}^{K} x_{if} \geq x_{jk} \quad \forall (i,j) \in P_{ij}; \forall k = 1,\ldots,K \tag{12}$$

$$x_{ik}, y_{ks}, U_k, Z_s, v_{iks} \in \{0,1\}; \forall i = 1,...,N; \forall k = 1,...,K; \forall s = 1,...,S \tag{13}$$

The values α and β can be estimated by the DMs. Equation (1) represents the objective function value of the integrated model where the first and the second terms aim to minimize the total cost of balancing and PF in terms of the installation costs of stations and supermarkets, respectively. Constraints (2) and (3) ensure that each task and each station are assigned to only one station and one supermarket, respectively. Using constraints (4) and (5) the number of established stations and supermarkets are calculated, respectively. Constraints (6) and (7) assure that before assigning tasks to stations and stations to supermarkets, respectively, the stations and supermarkets are established before. Constraints (8) and (9) indicate that the stations times and supermarkets' demands do not exceed the given CT and supermarket's capacity, respectively. Constraints (10) and (11) control the boundaries of the auxiliary variable. By constraint (12) we make sure that the precedence relationships between tasks are satisfied. Constraint (13) define the domain of the decision variables.

4. Computational results

To show the performance of the proposed integrated model, it is applied on a real case and some benchmarks taken from the ALB literature [12] using GAMS-CPLEX solver on a PC with Core i7 2.4 GHz processor and 8 GB RAM. Table 2 (a)-(c) shows the computational results of the proposed model considering the following scenarios: (a) a feasible ALB (Feasible M or FM) and an optimized number of supermarket (ONS) abbreviated by "FM+ONS"; (b) an optimized ALB (optimized M or OM) and a feasible number of supermarket (FNS) abbreviated by "OM+FNS"; (c) both number of stations and number of supermarkets are optimized abbreviated by "OM+ONS". In this table, Columns No., Problem, CT and Cap present the problem number, the problem name, the considered cycle time (CT) and the capacity of supermarkets (Cap), respectively. Column M^* shows the optimal number of stations which is available in the ALB literature. To show the performance of the proposed model over different problems, the optimized number of stations (M), the optimized number of supermarkets (NS), the total installation costs (TIC) of balancing and PF are reported. Also, since there is a trend in the ALB literature to show the efficiency of the resulting ALB problem, the balance efficiency (BE) and logistics efficiency (LE) percent which are calculated using Equations (14) and (15) are also reported. Also the CPLEX solver time in seconds are also reported under column CPU time.

$$BE\,(\%) = \frac{\sum_{i=1}^{N} t_i}{M \times CT} \tag{14}$$

$$LE\,(\%) = \frac{\sum_{i=1}^{N} d_i}{NS \times Cap} \tag{15}$$

The supermarket installation cost (β) associated with the considered supermarket capacity i.e. 50, 100, 150 are as 300, 500, 1000, respectively. Moreover, the station installation cost (α) is set to 1000.

Table 2(a). The computational results of the proposed integrated model for scenario *FM+ONS*

No	Problem	*CT*	*Cap*	*M**	*M*	*NS*	*TIC*	*BE(%)*	*LE(%)*	*CPU(s)*
1	Case	35	50	17	19	5	20500	78.1	80.8	107.3
2	study		100	17	19	3	20500	78.1	67.3	166.4
3			150	17	18	3	21000	82.5	44.9	21.6
4		40	50	16	18	5	19500	72.2	80.8	128.6
5			100	16	17	3	18500	76.4	67.3	126.4
6			150	16	17	2	19000	76.4	67.3	35.6
7	Jackson	7	50	8	11	1	11300	59.7	90.0	6.6
8			100	8	11	1	11500	59.7	45.0	9.1
9			150	8	11	1	12000	59.7	30.0	9.2
10		10	50	5	10	1	10300	46.0	90.0	6.8
11			100	5	10	1	10500	46.0	45.0	5.2
12			150	5	10	1	11000	46.0	30.0	2.0
13	Mitchell	15	50	8	9	3	9900	77.8	69.3	6.0
14			100	8	10	2	11000	70.0	52.0	10.3
15			150	8	10	1	11000	70.0	69.3	4.1
16		21	50	5	8	3	8900	62.5	69.3	10.9
17			100	5	8	2	9000	62.5	52.0	5.1
18			150	5	8	1	9000	62.5	69.3	8.7
19	Buxey	30	50	12	14	4	15200	77.1	89.0	82.7
20			100	12	14	2	15000	77.1	89.0	229.1
21			150	12	13	2	15000	83.1	59.3	127.4
22		36	50	10	11	4	12200	81.8	89.0	233.6
23			100	10	11	2	12000	81.8	89.0	155.9
24			150	10	11	2	13000	81.8	59.3	53.8
25	Sawyer	27	50	13	14	4	15200	85.7	78.5	288.5
26			100	13	15	2	16000	80.0	78.5	279.3
27			150	13	14	2	16000	85.7	52.3	217.7
28		33	50	11	12	4	13200	81.8	78.5	195.5
29			100	11	12	2	13000	81.8	78.5	120.4
30			150	11	12	2	14000	81.8	52.3	94.8
31	Gunther	41	50	14	15	4	16200	78.5	83.0	38.7
32			100	14	15	2	16000	78.5	83.0	197.9
33			150	14	15	2	17000	78.5	55.3	395.2
34		44	50	12	14	4	15200	78.4	83.0	7.1
35			100	12	13	2	14000	84.4	83.0	196.4
36			150	12	13	2	15000	84.4	55.3	252.2

Table 2(b). The computational results of the proposed integrated model for scenario *OM+FNS*

No	Problem	*CT*	*Cap*	*M**	*M*	*NS*	*TIC*	*BE(%)*	*LE(%)*	*CPU(s)*
1	Case	35	50	17	17	6	18800	87.3	67.3	148.7
2	study		100	17	17	4	19000	87.3	50.5	73.9
3			150	17	17	2	19000	87.3	67.3	22.2
4		40	50	16	16	6	17800	81.2	67.3	81.4
5			100	16	16	5	18500	81.2	40.4	56.5
6			150	16	16	3	19000	81.2	44.9	99.8
7	Jackson	7	50	8	8	1	8300	82.1	90.0	2.5
8			100	8	8	1	8500	82.1	45.0	5.6
9			150	8	8	1	9000	82.1	30.0	10.5
10		10	50	5	5	1	5300	92.0	90.0	3.0
11			100	5	5	1	5500	92.0	45.0	1.4

Table 2(b). The computational results of the proposed integrated model for scenario *OM+FNS*

No	Problem	*CT*	*Cap*	*M**	*M*	*NS*	*TIC*	*BE(%)*	*LE(%)*	*CPU(s)*
12			150	5	5	1	6000	92.0	30.0	2.6
13	Mitchell	15	50	8	8	4	9200	87.5	52.0	3.0
14			100	8	8	3	9500	87.5	34.7	9.3
15			150	8	8	2	10000	87.5	34.7	7.6
16		21	50	5	5	4	6200	100.0	52.0	1.2
17			100	5	5	3	6500	100.0	34.7	8.3
18			150	5	5	2	7000	100.0	34.7	5.0
19	Buxey	30	50	12	12	5	13500	90.0	71.2	56.0
20			100	12	12	3	13500	90.0	59.3	88.7
21			150	12	12	3	15000	90.0	39.6	248.0
22		36	50	10	10	5	11500	90.0	71.2	51.2
23			100	10	10	3	11500	90.0	59.3	67.5
24			150	10	10	3	13000	90.0	39.6	306.4
25	Sawyer	27	50	13	13	5	14500	92.3	62.8	89.5
26			100	13	13	3	14500	92.3	52.3	270.5
27			150	13	13	3	16000	92.3	34.9	87.5
28		33	50	11	11	5	12500	89.3	62.8	134.9
29			100	11	11	3	12500	89.3	52.3	283.5
30			150	11	11	3	14000	89.3	34.9	271.1
31	Gunther	41	50	14	14	5	15500	84.1	66.4	64.7
32			100	14	14	3	15500	84.1	55.3	372.1
33			150	14	14	3	17000	84.1	36.9	219.8
34		44	50	12	12	5	13500	91.5	66.4	93.8
35			100	12	12	3	13500	91.5	55.3	210.3
36			150	12	12	3	15000	91.5	36.9	98.8

Table 2(c). The computational results of the proposed integrated model for scenario *OM+ONS*

No	Problem	*CT*	*Cap*	*M**	*M*	*NS*	*TIC*	*BE(%)*	*LE(%)*	*CPU(s)*
1	Case	35	50	17	17	5	18500	87.3	80.8	14.7
2	study		100	17	17	3	18500	87.3	67.3	195.4
3			150	17	17	2	19000	87.3	67.3	20.6
4		40	50	16	16	5	17500	81.2	80.8	517.1
5			100	16	16	3	17500	81.2	67.3	369.1
6			150	16	16	2	18000	81.2	67.3	27.2
7	Jackson	7	50	8	8	1	8300	82.1	90.0	0.1
8			100	8	8	1	8500	82.1	45.0	0.1
9			150	8	8	1	9000	82.1	30.0	0.1
10		10	50	5	5	1	5300	92.0	90.0	0.2
11			100	5	5	1	5500	92.0	45.0	0.1
12			150	5	5	1	6000	92.0	30.0	0.1
13	Mitchell	15	50	8	8	3	8900	87.5	69.3	28.8
14			100	8	8	2	9000	87.5	52.0	3.6
15			150	8	8	1	9000	87.5	69.3	0.1
16		21	50	5	5	3	5900	100.0	69.3	50.5
17			100	5	5	2	6000	100.0	52.0	1.6
18			150	5	5	1	6000	100.0	69.3	0.1
19	Buxey	30	50	12	12	4	13200	90.0	89.0	207.7
20			100	12	12	2	13000	90.0	89.0	148.6
21			150	12	12	2	14000	90.0	59.3	33.4
22		36	50	10	10	4	11200	90.0	89.0	97.7
23			100	10	10	2	11000	90.0	89.0	88.8
24			150	10	10	2	12000	90.0	59.3	6.6
25	Sawyer	27	50	13	13	4	14200	92.3	78.5	275.5
26			100	13	13	2	14000	92.3	78.5	206.4
27			150	13	13	2	15000	92.3	52.3	4.8
28		33	50	11	11	4	12200	89.3	78.5	1296.1
29			100	11	11	2	12000	89.3	78.5	689.6
30			150	11	11	2	13000	89.3	52.3	234.2
31	Gunther	41	50	14	14	4	15200	84.2	83.0	1775.3
32			100	14	14	2	15000	84.2	83.0	88.9
33			150	14	14	2	16000	84.2	55.3	98.3
34		44	50	12	12	4	13200	91.5	83.0	2068.1
35			100	12	12	2	13000	91.5	83.0	36.4
36			150	12	12	2	14000	91.5	55.3	8.2

For all the problems solved the optimal solution have been found during the reported CPU time.

As one can observe, the resulting M, NS and TIC in Table 2(c) (scenario OM+ONS) are lower than their counterparts in Tables 2(a) (scenario FM+ONS) and 2(b) (scenario OM+FNS) for each problem. This is due to the simultaneous optimization of both M and NS is the proposed integrated model. Figures 2 to 4 compare the resulting M, NS and TIC, respectively, for each problem considering the three scenarios considered for the integrated model. According to these figures, the OM+ONS has resulted to a lower values for M, NS and TIC among the three scenarios.

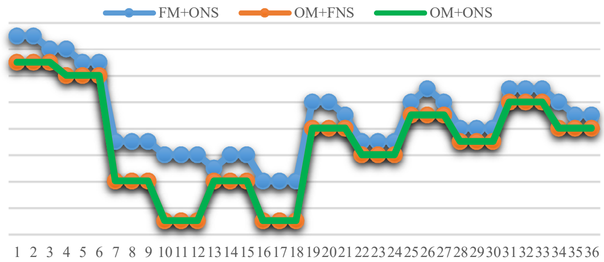

Fig. 2. Comparison of *M* for different problems and scenarios

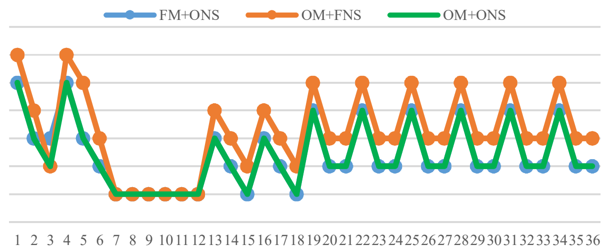

Fig. 3. Comparison of *NS* for different problems and senarios

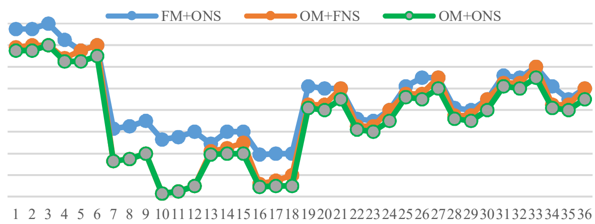

Fig. 4. Comparison of *TIC* for different problems and senarios

Fig. 5 compares the resulting TIC for different test problems and CT and supermarket capacity in the best scenario (OM+ONS). As Fig. 5 shows, by increasing the supermarket capacity the *TIC* has been subjected to changes which is mainly caused by different NS.

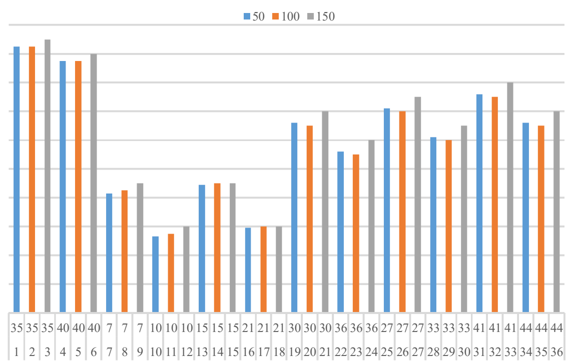

Fig. 5. Comparision of *TIC* for different problem, *CT* and supermarket capacity

Fig. 6 compares the resulting BE (%) and LE (%) for different test problems, CT and supermarket capacity in the best scenario. As this Fig. shows by increasing the supermarket capacity the LE has been subjected to variations due to changes in the optimal NS.

Table 3 shows the optimal combination of M, NS and supermarket capacity (Cap) for each problem and CT in the best scenario. This combination is achieved by selecting those M and NS in which TIC is minimized also both of the BE and LE measures are at their maximum levels. For example, for the case study with CT=35, the combination of M=17, NS=5, Cap=50, has resulted into the minimum TIC of 18500 while both BE and LE measures are also maximized.

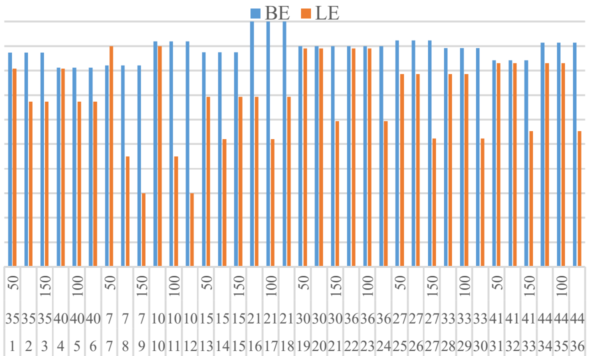

Fig. 6. Comparision of $BE(\%)$ and $LE(\%)$ for different problem, CT and supermarket capacity for the best scenario

Table 3. The optimal combination of M, NS and supermarket capacity for each problem and CT

Problem	CT	M	NS	Cap		
				50	100	150
Case study	35	17	5	18500		
	40	16	5	17500		
Jackson	7	8	1	8300		
	10	5	1	5300		
Mitchell	15	8	3	8900		
	21	5	3	5900		
Buxey	30	12	2		13000	
	36	10	2		11000	
Sawyer	27	13	2		14000	
	33	11	2		12000	
Gunther	41	14	2		15000	
	44	12	2		13000	

In summary, according to the obtained results it can be verified that the proposed integrated model is capable of finding the optimal number of stations and supermarkets from balancing and PF aspects, respectively. Also, another measures in selecting the optimal combination of stations and supermarkets aside from TIC is the balancing and logistics efficiencies.

5. Conclusion

It is believed that the assembly line balancing (ALB) and parts feeding (PF) problems are interdependent decision problems where their simultaneous planning can result in more potential gains. On the hand, considering nowadays complex and competitive manufacturing environment, recently there has been a growing trend towards using supermarkets in PF. They are applied as decentralized storages near the assembly lines (ALs). Thus, in this study an integrated model was proposed to deal with both ALB and PF using supermarkets. The objective function considered was the total installation costs regarding the number of stations and the number of supermarkets. The computational results over a case study and some benchmarks taken form ALB literature showed that the proposed model can optimize the total installation costs of AL while the CT and the supermarket capacities are satisfied.

As a future research direction, developing the proposed model so that both installation and shipment costs are dealt with in PF using supermarkets, can be considered. Furthermore, due to the complexity of the resulting integrated model, proposing efficient metaheuristics to be able to solve larger test problems, can be another future research direction. Moreover, other types of AL configuration such as U-shaped lines rather than simple ALs can be taken into consideration. Moreover, generalizing the current model to be able to consider the real-world environment such as the existence of different bin sizes or constraints on the assignment of stations to the supermarkets should be further considered.

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