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A mathematical model for supermarket location problem with stochastic station demands

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Abstract

This paper aims to investigate the effect of station demands variations on supermarket location problem (SLP). This problem arises in the real-world assembly line part feeding (PF) context where supermarkets are used as the intermediate storage areas for stations. To this purpose a stochastic SLP model is developed to optimize the total cost of PF in terms of shipment, inventory and installation costs. The computational results over a real case as well as different test instances verify that the station demands variation has an effect on the SLP solutions.

Keywords: deterministic; stochastic; part feeding; supermarket; optimization

1. Introduction

In the past few decades, many manufacturers have adopted the mass customization concept to be able to respond the customers' individual needs. Accordingly, the part feeding (PF) of such manufacturing systems have to be carefully designed so that the possibility of stations starvation and line-side inventory are minimized. Just-in-Time (JIT) philosophy suggests frequent delivering of small amounts of parts to the stations, rather than in bulk over long periods. Using the past feeding policies, parts had to be delivered from a central warehouse. However, recently supermarkets are used as the decentralized storage areas near the assembly lines (ALs) to enable a flexible and reliable JIT part supply of stations [1]. In this regard, tow trains are used to feed the parts to stations in bins through their regular visits. Using this feeding policy, the total inventory around the stations will decrease while the visit frequency of stations from supermarkets increases. However, since the space is scarce and valuable on the shop floor, determining the number and the location of supermarkets, called the supermarket location problem (SLP), has been considered as a long-term decision problem of PF using supermarkets [2]. According to the authors' best knowledge, a very few studies have been performed in the SLP literature. Recently, an Integer Programming for SLP was proposed by [3] as well as a Genetic Algorithm (GA) to optimize the total shipment and installation cost of supermarkets while assuming the stations' demands to be deterministic. However, the authors did not consider the effect of the number of supermarkets on the inventory cost associated with the stock level of the supermarket(s) that the stations are feeding from.

On the other hand, in real life, there are different sources of variation such as variability of station demand which can results in line stoppages, shortages, overtime, etc. in case of high variations [4]. Thus, this study aims to investigate the effect of station demand variations on SLP by proposing a stochastic SLP model in which the shipment, the inventory and the installation costs of supermarkets are optimized, simultaneously. The proposed model is applied on a real case as well as a set of test instances. The computational results are

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compared to the deterministic model existing in the literature [3]. The reminder of this paper is organized as follows. Section 2 reviews the SLP literature. Section 3 presents the real case explanation and problem description. Section 4 presents the results and discussions. Finally the conclusions and future research directions are provided in Section 5.

2. Literature review

Although the warehouse location problem was extensively studied in the literature, the problem of determining the optimum number of supermarkets as well as their locations have been scarcely considered within the in-house logistics context [5,6]. Battini et al. [7] proposed a step-by-step decision support procedure to determine the degree of centralization/decentralization in terms of transportation and inventory costs. However, they assumed that a supermarket can feed several ALs while many real-world manufacturers employ several supermarkets feeding the same AL. Emde and Boysen [1] proposed that supermarkets can be established in any place around the stations. However, in practice, there are places that cannot be occupied by supermarkets since they are used by other facilities. Alnahhal and Noche [3] proposed an efficient GA 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. They also proposed a mathematical formulation and compared the performance of GA to optimize the total transportation and installation cost while assuming the stations' demands to be deterministic. However, they did not consider the effect of number of supermarkets on the inventory cost associated with the stock level of the supermarkets feeding the stations. Recently, Battini et al. [8,9] have jointly addressed line balancing and PF problems where direct and indirect PF policies as well as ergonomic considerations were taken into account while modeling both problems. The readers interested in more details on the part logistics and their related decision problems are referred to Boysen et al. [10]. This study is a very first attempt in the literature to propose a stochastic mathematical model for SLP in which the total cost of part feeding including the shipment, inventory, and installation cost of supermarkets are optimized, simultaneously. Moreover, unlike the existing literature (e.g., [3]) the inventory cost of the safety stocks required by the supermarkets to respond to the stations demand variation is considered in addressing the SLP.

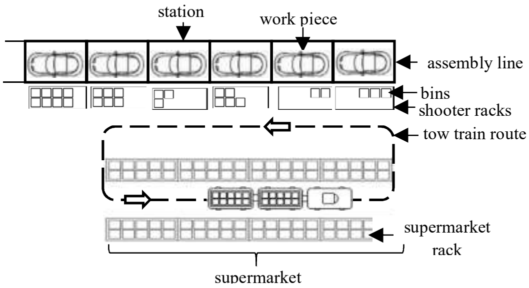

Fig. 1. The layout of an AL using supermarket

3. Problem description and model formulation

This study is motivated by a real-world AL where a new model of a car part is going to be produced. Since this specific part has a high demand rate and certain preparations are required before the final assembly of this part in the stations, the decision makers (DMs) aim to apply the supermarkets concept and use tow trains to supply the stations through regular visits.

The AL under study is a single straight line where stations $k = 1,\dots,K$ have to be supplied with sd_k bins of parts from supermarkets. The coordinate of stations on the AL are defined by (x_k, y_k) whereas the supermarket locations are shown by (X_s, Y_s); $s = 1,\dots,S$ ($S =$ maximum supermarket number). The distance that tow trains travel to supply bins to stations can be calculated based on the distance between supermarkets to stations, from station to station and back from station to supermarket. Fig. 1 shows a layout of an AL which uses supermarket to deliver bins to the shooter racks of stations through tow trains' regular visits.

Considering the described assembly line and material supply process at the company, this study aims at finding the best number and location of supermarkets through solving the SLP. The SLP targets at selecting the optimum number and location of supermarkets from a set of places and also the stations that should be fed with material from each supermarket considering some assumptions so that the transportation, inventory and installation costs of supermarkets are minimized. The main assumptions of the SLP are [3]: 1) The tow trains set off from supermarket to feed the stations according to a fixed schedule which is equal to lead time, 2) The shipment cost is related to the distance traveled by the tow train to supply the stations with the mean of the stations demands, 3) The inventory cost is related to the holding cost of the safety stock required by the supermarkets to respond to the stations' demand variations over the fixed replenishment interval and not to the operative stocks used by each station [7], 4) 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, 5) There are candidate supermarkets places where the optimum number and location of supermarkets has to be chosen from, 6) The capacity of supermarkets serving the stations is limited and when this limit is reached another possible supermarket position has to be opened [1,3], 7) Parts are sorted and delivered in bins which are all identical in term of dimensions [6,11], 8) As the stations are considered to be arranged in a straight pattern in this study, it is also true to assume that the location of supermarkets can be determined as close as possible to the stations depending on the space limitation of the shop floor. Thus, the supermarket location is determined to be smoothly scattered next to the shooter racks of stations [1].

The notations shown in Table 1 are used for modeling the stochastic SLP.

Table 1. List of notations.

Notation	Definition
k,l:	Stations index (k,l = 1, … ,K)
s:	Supermarket index (s = 1, … ,S)
x_k, y_k:	x and y-coordinates of station k
$dist_{skl}$:	Total distance traveled by tow train from supermarket s to supply all stations from stations k to l; $dist_{skl} = \lvert X_s - x_k\rvert + \lvert Y_s - y_k\rvert + \lvert x_k - x_l\rvert + \lvert y_k - y_l\rvert + \lvert X_s - x_l\rvert + \lvert Y_s - y_l\rvert$
sd_k:	Demand of station k in terms of number of bins; $sd_k \sim N(sd\mu_k, sd\sigma_k^2)$
z_{skl}:	$\begin{cases} 1; & \text{if all stations from station } k \text{ to station } l \text{ are fed by supermarket } s \\ 0; & otherwise \end{cases}$
Cap_s:	Capacity of supermarket s (number of bins)
Dsd_{kl}:	Total standard deviation of part demand for all stations from stations k to l; $Dsd_{kl} = (\sum_{f=k}^{l} sd\sigma_f^2)^{1/2}$
IC:	Installation cost of one supermarket
$INVC$:	Inventory cost of holding one bin during the stations replenishment interval
LT:	Lead time to replenish station (a fraction of the shift time)
M:	Number of stations
NS:	Optimized number of supermarkets
S:	Maximum supermarket number
SC:	Shipment unit cost of moving one bin one unit distance
TC:	Total cost of part feeding
$Tdem_{kl}$:	Total demand of all stations from station k to station l; $Tdem_{kl} = \sum_{f=k}^{l} sd\mu_f$
X_s,Y_s:	x and y-coordinates of supermarket s
α:	Upper bound for the probability of station demands exceed the supermarket capacity
β:	The confidence (or safety) level (β =1-α)

According to the assumptions given above, the following formulation of the stochastic SLP model is proposed:

$$Min\ TC = \sum_{s=1}^{S}\sum_{k=1}^{M}\sum_{l=k}^{M} SC \times Tdem_{kl} \times dist_{skl} \times z_{skl} + \sum_{s=1}^{S}\sum_{k=1}^{M}\sum_{l=k}^{M} INVC \times Z_{1-\beta} \times Dsd_{kl} \times \sqrt{LT} \times z_{skl} + NS \times IC \quad (1)$$

$$\sum_{s=1}^{S}\sum_{k=1}^{M}\sum_{l=k}^{M} z_{skl} = NS \quad (2)$$

$$\sum_{s=1}^{S}\sum_{k=1}^{b} z_{skb} = \sum_{s=1}^{S}\sum_{l=b+1}^{M} z_{s(b+1)l} \qquad \forall\, b = 1,\dots,M-1 \quad (3)$$

$$\sum_{k=1}^{M}\sum_{l=k}^{M} z_{skl} \le 1 \qquad s = 1,\dots,S \quad (4)$$

$$(Tdem_{kl} + Z_{1-\beta} \times Dsd_{kl}) \times z_{skl} \le Cap_s \quad (5)$$

$$NS \ge 1\ and\ integer \quad (6)$$

$$z_{skl} = 0\ or\ 1 \quad \forall s = 1,\dots,S,\ \forall k = 1,\dots,M,\ \forall l = k,\dots,M \quad (7)$$

The values SC, IC, $INVC$ and LT can be estimated by the DMs. Equation (1) represents the objective function value of SLP where the first, the second and the third terms aim to minimize the total shipment, inventory and installation costs of part feeding using supermarket, respectively. Constraint (2) ensures that the number of station groups (cells) is equal to the number of supermarkets. By constraint (3) we make sure that all cells are supplied by supermarkets. Constraint (4) ensures that each station is fed by only one supermarket. By constraint (5) we assure that the capacity of the supermarket is sufficient not just for the average demand but also for its upper limit calculated by adding $Tdem_{kl}$ to the standard deviation of stations demand (Dsd_{kl}) for each supermarket multiplied by $Z_{1-\beta}$, which is the 1-β quantile of the standard normal distribution. Constraint (6) prevents the variables to be equal to zero due to minimization in the objective function. Constraint (7) defines the binary variables.

4. Results and discussion

To show the performance of the proposed stochastic SLP model, it is applied on a real case as well as some generated test instances, using GAMS-CPLEX solver. To investigate the effect of station demands variations on SLP, the results obtained by the proposed SLP model are compared in terms of S(maximum supermarket number), NS(optimized number of supermarkets), TSC (Total shipment cost), $TINVC$ (total inventory cost) and TIC (total installation cost) for the deterministic and stochastic models with different safety levels, i.e., β =0.9, 0.95 and 0.975, as shown in Tables 2 to 5.

Considering the stochastic nature of stations' demand, safety level is considered in this study to assure that the total demand of stations assigned to each supermarket will not exceed the supermarket capacity. For instance, safety level of 0.9 (β= 0.9) means that with 90% confidence level the total demand will not exceed the supermarket's capacity. The safely levels are chosen in consultation with experts at industry and reviewing the related literature (e.g., [12,13]). It is worthy to mention that when we set $Z_{1-\beta}$=0, the stochastic model obtains the results of the deterministic model since by setting the normal coefficient ($Z_{1-\beta}$) equal to zero the corresponding stochastic terms will be omitted from the model objectives as well as constraints.

As these tables show aside from the case study (problem with 25 stations), different test instances, which are categorized into three problem sizes (i.e. small, medium and large), are generated where their number of stations are shown in column "Stations #." Considering the normal distribution for stochastic station demand (in bins), the means and the variances of the station demands, i.e. $sd\mu_k$ and $sd\sigma_k^2$ are calculated using $U(1,10)$ and $U(0,(sd\mu_k/2)^2)$, respectively. Column "Cap" shows the capacity of supermarket. The installation cost (IC) associated with the considered supermarket capacity, i.e. 50, 100, 150, 200 and 250 are 300, 500, 1000, 2000 and 3000, respectively. It is assumed that the stations are uniformly arranged along a straight line in an ascending order with one distance unit from each other. Moreover, the supermarkets candidate places, shown by x_s, are smoothly positioned in the range of stations locations. For simplicity y_k and Y_s values are set to 0 and 5, respectively. The SC, $INVC$ and LT values are set to 1, 50 and 0.25, respectively. The maximum supermarket number (S) for the considered supermarket capacities are obtained through dividing the sum of the upper limits of workstations demand (i.e. $\sum_{k=1}^{M} sd\mu_k + Z_{1-\beta}\sqrt{sd\sigma_k^2}$) to the supermarket capacities added by 3 to allow the SLP model to search throughout a feasible and reasonable search space.

Table 2. SLP results for deterministic model

Size	No.	Station #	*Cap*	*S*	*NS*	*TSC*	*TINVC*	*TIC*
Small	1	25	50	7	5	3250	0	1500
	2		100	5	4	3732	0	2000
	3		150	5	3	4492	0	3000
	4		200	4	2	6034	0	4000
	5		250	4	2	6034	0	6000
	6	40	50	8	8	4050	0	2400
	7		100	6	6	4808	0	3000
	8		150	5	4	6300	0	4000
	9		200	5	3	7798	0	6000
	10		250	4	3	7798	0	9000
Medium	11	60	50	11	11	6890	0	3300
	12		100	7	7	9164	0	3500
	13		150	6	6	10204	0	6000
	14		200	5	5	11658	0	10000
	15		250	5	4	13860	0	12000
	16	80	50	13	13	9700	0	3900
	17		100	8	8	13400	0	4000
	18		150	7	7	14774	0	7000
	19		200	6	6	16614	0	12000
	20		250	5	5	19140	0	15000
Large	21	100	50	15	15	12496	0	4500
	22		100	9	9	17690	0	4500
	23		150	7	7	21416	0	7000
	24		200	6	6	24244	0	12000
	25		250	6	6	24244	0	18000

Table 3. SLP results for $Z_{1-\beta} = 1.2816$.

Size	No.	Station #	*Cap*	*S*	*NS*	*TSC*	*TINVC*	*TIC*
Small	1	25	50	8	5	3304	1130	1500
	2		100	6	4	3738	1000	2000
	3		150	5	3	4492	866	3000
	4		200	5	2	6034	717	4000
	5		250	4	2	6034	717	6000
	6	40	50	9	7	4360	1290	2100
	7		100	6	6	4808	1190	3000
	8		150	5	4	6300	986	4000
	9		200	5	3	7798	853	6000
	10		250	5	2	10800	697	6000
Medium	11	60	50	12	11	6910	1931	3300
	12		100	8	8	8384	1676	4000
	13		150	6	6	10204	1447	6000
	14		200	6	5	11658	1325	10000
	15		250	5	4	13860	1190	12000
	16	80	50	15	14	9314	2374	4200
	17		100	9	9	12324	1937	4500
	18		150	7	7	14778	1695	7000
	19		200	6	6	16614	1586	12000
	20		250	6	5	19140	1436	15000
Large	21	100	50	18	18	9109	3115	5400
	22		100	11	11	15322	2458	5500
	23		150	8	8	19336	2104	8000
	24		200	7	7	21416	1959	14000
	25		250	6	6	24244	1819	18000

Table 4. SLP results for $Z_{1-\beta} = 1.6448$.

Size	No.	Station #	*Cap*	*S*	*NS*	*TSC*	*TINVC*	*TIC*
Small	1	25	50	8	6	2968	1579	1800
	2		100	6	4	3750	1269	2000
	3		150	5	3	4492	1111	3000
	4		200	5	2	6034	920	4000
	5		250	4	2	6034	920	6000
	6	40	50	9	7	4360	1655	2100
	7		100	6	5	5400	1413	2500
	8		150	5	4	6300	1266	4000
	9		200	5	3	7798	1095	6000
	10		250	5	2	10800	895	6000
Medium	11	60	50	13	11	6902	2494	3300
	12		100	8	8	8384	2151	4000
	13		150	7	6	10204	1858	6000
	14		200	6	5	11658	1700	10000
	15		250	5	4	13860	1527	12000
	16	80	50	16	14	9310	3071	4200
	17		100	10	10	11480	2598	5000
	18		150	8	8	13412	2324	8000
	19		200	7	6	16614	2035	12000
	20		250	6	5	19140	1843	15000
Large	21	100	50	19	17	8830	3895	5100
	22		100	11	11	15322	3154	5500
	23		150	9	9	17698	2845	9000
	24		200	7	7	21416	2514	14000
	25		250	7	6	24244	2334	18000

Table 5. SLP results for $Z_{1-\beta} = 1.96$.

Size	No.	Station #	*Cap*	*S*	*NS*	*TSC*	*TINVC*	*TIC*
Small	1	25	50	8	6	2968	1882	1800
	2		100	6	4	3750	1512	2000
	3		150	5	3	4492	1324	3000
	4		200	5	2	6034	1097	4000
	5		250	4	2	6034	1097	6000
	6	40	50	10	7	4360	1972	2100
	7		100	7	5	5400	1683	2500
	8		150	6	4	6300	1508	4000
	9		200	5	3	7798	1305	6000
	10		250	5	2	10800	1067	6000
Medium	11	60	50	13	11	6894	2985	3300
	12		100	8	8	8384	2563	4000
	13		150	7	6	10204	2214	6000
	14		200	6	4	13862	1817	8000
	15		250	5	4	13862	1817	12000
	16	80	50	16	14	9320	3672	4200
	17		100	10	10	11480	3096	5000
	18		150	8	8	13412	2769	8000
	19		200	7	6	16614	2425	12000
	20		250	6	5	19140	2196	15000
Large	21	100	50	19	18	8810	4782	5400
	22		100	11	11	15338	3742	5500
	23		150	9	9	17698	3391	9000
	24		200	7	7	21416	2996	14000
	25		250	7	6	24244	2781	18000

Fig. 2 compares the resulting NS for different safety levels and test problems. As Fig. 2 shows in 13 out of 25 problems, about 50% of problems, the NS values obtained through different safety levels have been subjected to changes, where in 9 out of 13 instances the NS values have been increased while in the rest of instances (i.e. 4 instances) the NS values have been decreased.

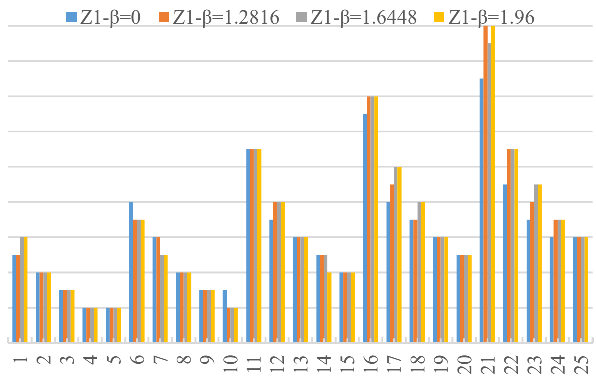

Fig. 2. Comparison of NS for different safety levels.

Fig. 3 compares the resulting $TINVC$ for different safety levels. As one can observe there is no inventory cost when the deterministic demands are considered. However, when station demands are stochastic, the amount of $TINVC$ has strictly increased in line with the safety level improvement. Furthermore, the comparison of TC for different safety levels are illustrated in Fig. 4. The TC has strictly raised when there is an increase in the safety level.

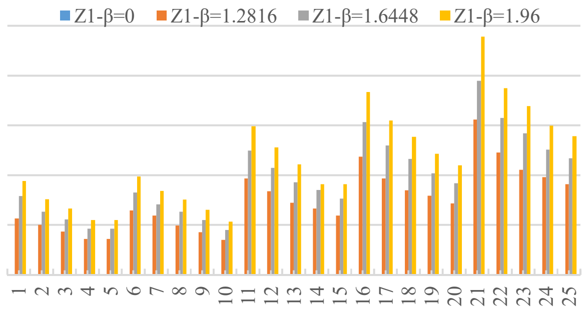

Fig. 3. Comparison of $TINVC$ for different safety levels.

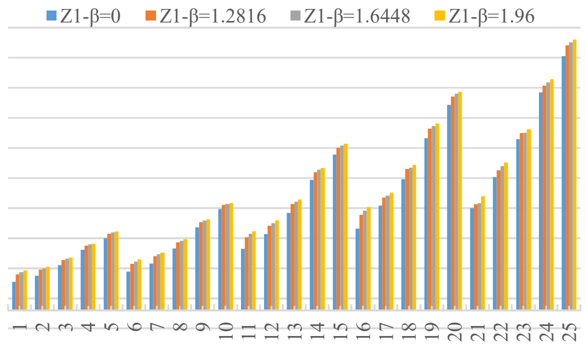

Fig. 4. Comparison of TC for different safety levels.

For the real case, i.e. the problem with 25 stations, the NS has raised to 6 when the safety level has increased to 0.95 and 0.975 for the supermarket capacity of 50. Moreover, when safety level increases the TC has raised particularly due to the rise of $TINVC$.

Table 6 shows the percent of deviations for different problem sizes and measures. For instance, considering the S measure for small problems, in 57% of the small test instances considered (i.e. 10), the S values obtained through setting $Z_{1-\beta}$ equal to 1.28, 1.64 and 1.96 have been subjected to deviation from the S value by the deterministic model. The rest of the data in this table follow the same description.

Table 6. Percent of deviations for different performance measures and problem sizes

Size	*S*	*NS*	*TSC*	*TINVC*	*TIC*	*TC*
Small	57	33	47	100	33	100
Medium	80	40	57	100	40	100
Large	93	80	80	100	80	100
Total	73	45	57	100	45	100

Table 7 shows the percentages of equality, increase and decrease of the performance measures over different problem sizes where the deterministic and stochastic models' results are compared. For instance, for the S performance measure in small problem instances, in 43 percent of the total small instances (i.e. 30), the S values obtained by the stochastic models over different safety levels (i.e. β=0.9,0.95 and 0.975), have resulted to the same S value obtained by the deterministic model. Accordingly, the percent of increase in this measure when the results of stochastic models are compared with the deterministic model, equals to 57%. Finally, considering the above comparison, the percent of decrease in S measure is zero.

Table 7. Percentages of equality, increase and decrease of the performance measures over different problem sizes

Performance measures	Problem	Equality	Increase	Decrease
S	Small	43	57	0
	Medium	20	80	0
	Large	7	93	0
	Total	27	73	0
NS	Small	67	7	27
	Medium	60	37	3
	Large	20	80	0
	Total	55	33	12
TSC	Small	53	40	7
	Medium	43	20	37
	Large	20	0	80
	Total	43	24	33
TINVC	Small	0	100	0
	Medium	0	100	0
	Large	0	100	0
	Total	0	100	0
TIC	Small	67	7	27
	Medium	60	37	3
	Large	20	80	0
	Total	55	33	12
TC	Small	0	100	0
	Medium	0	100	0
	Large	0	100	0
	Total	0	100	0

According to Table 7, one can observe that the station demand variations can affect the S, NS and the total cost of PF in terms of shipment, inventory and installation costs. In total, the percent of increase and decrease in NS are 33% and 12%, respectively. The percent of increase and decrease for TSC in total are 24% and 33%, respectively. For $TINVC$, there is 100% increase in all the solved problems. For TIC, the percent of increase and decrease are 33% and 12%, respectively. Finally, the percent of increase in TC is 100%, in all the problems. Considering the above results for the real case, they have been delivered to the industrial partner and validated by the experts. The company is now doing some experiments with the model to find the most cost-efficient solution with an acceptable service level.

5. Conclusion

Considering nowadays complex and competitive manufacturing environment, there has been recently a growing trend towards using supermarkets. Supermarkets are applied as decentralized storages near the assembly lines (ALs) to supply the parts to the stations in a flexible and reliable pattern through the tow trains regular visits. Due to the scarceness of the space on the shop floor, determining the optimum number and the locations of supermarkets, which is known as supermarket location problem (SLP), is an important challenge for many manufacturers. Although, considerable attempt has been made by researchers to solve the SLP in recent years. However, variability of station demand and its impact on the supermarket location has been ignored in the previous studies. Moreover, the inventory cost associated with the supermarkets are disregarded in the literature. In such circumstance, this study investigated the effect of station demand variations on SLP by proposing a stochastic SLP model in which the shipment, the inventory and the installation costs of supermarkets are optimized, simultaneously.

To this purpose a real case as well as some generated test instances were solved and the results were compared in terms of different safety levels as well as supermarket capacities. The computational results verified that the proposed model can be applied to optimize the SLP in terms of shipment, inventory and installation costs while the station demands are stochastic. Moreover, unlike the existing SLP model, the inventory cost associated with the supermarkets is considered. Overall, using the proposed stochastic model, the decision makers in real-world ALs can evaluate the possible effects of station demands variations on the SLP and accordingly find the solutions in which a trade-off between the safety levels and the total cost of part feeding occurs.

This study assumed that the station demands follow a normal distribution, however as a future research direction other types of distributions can also be considered. Moreover, extending the current model to handle more complex ALs by considering different bin sizes or constraints on the assignment of stations to the supermarkets or different delivery equipment, may also be considered in the future studies.

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