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Research Paper

A Mixed Integer Nonlinear Programming for Facility Layout Problem with Maintenance Constraints

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Abstract

The facility layout problem (FLP) is a well-known optimization problem that seeks to arrange the layout of production units or facilities generally towards less cost and considering some adjacency factor between the facilities. The adjacency factor mainly represents the material handling costs. In this research, a novel multi-objective mixed integer nonlinear programming (MINLP) model for the single-floor facility layout problem is developed. The model, unlike the current literature, considers some maintenance measures in addition to the classical adjacency factor. Firstly, some facilities need a certain amount of maintenance space around them. If this space is violated, some penalty would apply. Secondly, some facilities could have emergency maintenance requirements for which easy access from the entrance edges is necessary. This accessibility measure is optimized in the model. The validity of the proposed MINLP model is analyzed via simulation. The results show that if material handling costs are minimized, the maintenance measures will deviate approximately 100% of their optimal values. Moreover, if maintenance measures are optimized, the material handling cost will deviate around 50% of its optimal value. Both, classic and maintenance related measures show more sensitivity in dense and crowded production environments.

Keywords

Location, Accessibility, MINLP, Multi-objective, Single-floor

1. Introduction

Facility layout problem (FLP) is a well-known manufacturing oriented problem, which seeks to optimize the location and layout of units in order to increase productivity. Reduction of material handling costs, work in process, safety issues and lead times, more effective use of space, and flexibility to future changes are examples of productivity increase [1]. FLP has many applications such as layout design for manufacturing systems, airports, warehouses, hospitals, and schools, printed circuit board design, VLSI, semiconductor manufacturing, logistic design, chemical processes design, construction projects, backboard wiring problems, and hydraulic turbine design [2].

The focus of the researchers in this area have been on the manufacturing applications. The reason for this focus is rooted in the fact that material handling costs constitute 20% to 50% of the total operating expenses in manufacturing systems [3,4]. On the other hand, material handling costs are mainly dependent on the amount of flow and distances between facilities [5] which in turn is drastically affected by the layout and location of facilities and units. As a result, minimizing the material handling cost has been considered as the most popular objective in the literature.

Although objective functions other than minimization of materials handling costs are also considered by researchers, the use of maintenance related objectives or general implications in location and layout problems are not that common [6, 7]. When considering applying the FLP model to optimizing the layout and location of production facilities in a manufacturing system, this type of objective function or implication is quite rare [8-11]. To the best of our knowledge, only four papers studied this line of work. Table 1 demonstrates the properties of these researches. Although authors in [9] and [11] considered some maintenance related issues in their model, none of them optimized the layout towards maintenance criteria. This research aims to fill this gap by introducing some maintenance related features to the objective function of the FLP model.

Table 1. Description of pertinent researches considering maintenance and location simultaneously

Reference number	Optimizing layout for maintenance/ considering maintenance	Type of maintenance feature(s) optimized or considered	Type of model	Solution approach
[8]	none	periodic inspection intervals are optimized	probabilistic model and simulation model	analytical method and simulation
[9]	considered	preventive maintenance (PM) and corrective maintenance (CM) are considered (not optimized)	no explicit mathematical model (verbal model is used)	Genetic Algorithm
[10]	none	optimized maintenance schedules	relevant simulation modules are developed	-
[11]	considered	accessibility	-	comparative study via statistical methods

The rest of this paper is structured as follows. In Section 2, the basic concept of the maintenance related feature of this research is introduced in mathematical terms. In section 3, the multi-objective MINLP model is developed. Section 4 is devoted to the analysis and validation of the model. Finally, Section 5 provides conclusions and some research directions for future studies.

2. Insights into the incorporation of maintenance in FLP

When considering maintenance issues in determining the location of units, the following cases may come to mind. The function and operation of some facilities may harm the safety, performance, and failure rate of other facilities. Hence, these facilities should be located as far as possible. This could be achieved by revising the adjacency matrix of the problem accordingly.

Some facilities might have frequent urgent maintenance needs. For example, due to high temperature, it is common for some units in refineries to fail frequently because of fire or minor explosions or eruptions. In addition to placing automatic safety and maintenance equipment on site, it is also important to provide a high enough level of accessibility to these facilities via an appropriate layout design. This accessibility is a factor that ensures on-time human presence in emergencies and important failures.

Index of accessibility has already been used in locating components of systems [6]. The same idea may be modified for the facility layout model for manufacturing centers. In Figure 1, four units have been located in a rectangular area with two doors on the right and upper edges. Accessibility index of unit 1 in +x direction (door 1) could be denoted by A_x and defined as the number of units blocking access to the unit from door 1. Hence $A_x = 2$ and identically $A_y = 1$ for door 2. The total accessibility index of unit 1 may be thought of as $min(A_x, A_y) = 1$ expressing that unit 1 can be reached from outside (either door) by surpassing just one unit.

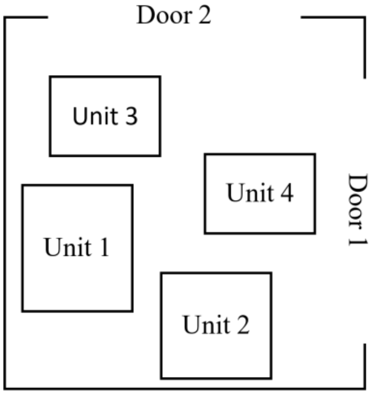

Figure 1. A display of the concept of accessibility through two doors

Production facilities and units might need enough free space around them for maintenance operations to take place conveniently. One might think of overstating the size of units in the location phase to ensure the availability of this maintenance space. However, when the available space is small, a better strategy would be to incorporate some penalty proportional to the importance of the unit for violating this free space.

Assume d_{ij} is the distance between units *i* and *j*. Operational maintenance space of unit *i* with unit *j* can be defined by equation 1 [6].

$$M_{ij} = \begin{cases} 1 & d_{ij} < d_{i,min} \\ \dfrac{d_{i,max} - d_{ij}}{d_{i,max} - d_{i,min}} & d_{i,min} \leq d_{ij} \leq d_{i,max} \\ 0 & d_{ij} > d_{i,max} \end{cases} \qquad (1)$$

According to the equation, if d_{ij} is more than a pre-specified maximum ($d_{i,max}$) the maintenance space for unit *i* is not violated by unit *j* ($M_{ij} = 0$). However, if d_{ij} is less than a pre-specified minimum ($d_{i,min}$) the maintenance space for unit *i* is violated by unit *j* ($M_{ij} = 1$). Any value for d_{ij} between the two specified extremums, results in a proportional value between zero and one for M_{ij}. Some weight factor may then be applied to M_{ij} and contribute to computing $M_i = \sum_{j \neq i} M_{ij}$ as the maintenance space index of unit *i*.

Finally, it might be like some facilities to be located in special places such as the corners or edges. Access to fresh air, sunlight, or some infrastructure may be the cause for this necessity amongst others. The special constraint should be incorporated in the model to ensure this location entailment takes place.

3. Mathematical model

In any FLP, the nature of distance between units should be specified first. Many industrial applications entail either Euclidean or rectilinear distances. In general, the lp-norm distance meter may be defined [8]. In this research, the rectilinear or Manhattan distance meter is considered due to its practicality. According to this meter, the distance between units *i* and *j* in 2D space is defined by equation 2.

$$d_{ij} = |x_i - x_j| + |y_i - y_j| \quad (2)$$

It is assumed that a rectangular area with known dimensions is considered for locating all the units. Each unit is also a rectangle with known dimensions. Moreover, distances are computed center to center. In other words, (x_i, y_i) is the coordinate of the center of unit *i* in Equation 2.

3.1 Parameter definition

Parameters of the mathematical model are defined as follows:

- Tlx and Tly : length and width of the available area i.e. location area
- lx_i and ly_i : length and width of unit *i*
- min_pdr_{ij} : the minimum pairwise distance required between units *i* and *j*
- max_pdr_{ij} : maximum pairwise distance allowed between units *i* and *j*
- $w\_min\_dist_{ij}$: penalty for each unit of violation of min_pdr_{ij}
- $w\_max\_dist_{ij}$: penalty for each unit of violation max_pdr_{ij}
- n_dr_i : minimum distance required around unit *i* for maintenance operation
- n_mopr_i : average yearly number of maintenance operation for unit *i*
- $dr_i = \begin{cases} 1 & if\ a\ door\ exist\ in\ the\ ith\ edge\ of\ the\ area \\ o & otherwise \end{cases}$ *i=1,2,3 and 4*

Parameters min_pdr_{ij} and max_pdr_{ij} define the ideal interval for d_{ij}. One can imagine that if units *i* and *j* are too close ($d_{ij} < min\_pdr_{ij}$), they might harm each other. The effect may be in the form of an increased failure rate or decreased production rate. On the other hand, there might be a heavy flow of material between units *i* and *j* which calls for them to be close ($d_{ij} \leq max\_pdr_{ij}$). This reflects the adjacency nature of FLP. In our model d_{ij} may violate the above interval. For each unit of the violation, a penalty is incurred in the objective function according to $w\_min\_dist_{ij}$ and $w\_max\_dist_{ij}$.

n_dr_i is the minimal required operational maintenance space around unit *i*. If other units are located too close to *i*, for each unit of violation of n_dr_i, a penalty is incurred in the objective function. Logically, the penalty must be more if unit *i* has a high failure rate and thus need more maintenance interventions. Hence, n_mopr_i is used as this penalty factor.

In this research, we have numbered edges of the location area according to bottom, right, top and left order. Theoretically, any of the edges can have a door in place. In this way, if for example, a door exists in the bottom edge, $dr_1 = 1$ and all the units could be accessed for maintenance from the bottom edge.

3.2 Decision variables

The model of this research includes the following variable:

- d_{ij} : the rectilinear distance between units *i* and *j*
- sx_i and sy_i: coordinates of the starting point of unit *i*
- ex_i and ey_i: coordinates of the ending point of unit *i*
- $fx_{ij} = \begin{cases} 1 & if\ sx_j \geq ex_i \\ 0 & otherwise \end{cases}$
- $fy_{ij} = \begin{cases} 1 & if\ sy_j \geq ey_i \\ 0 & otherwise \end{cases}$
- $x_{ij} = \begin{cases} 1 & if\ \ fx_{ij} = 1\ and\ fy_{ji} = fy_{ij} = 0 \\ 0 & otherwise \end{cases}$
- $y_{ij} = \begin{cases} 1 & if\ \ fy_{ij} = 1\ and\ fx_{ji} = fx_{ij} = 0 \\ 0 & otherwise \end{cases}$
- pdr_{ij} : pairwise distance requirement index between units *i* and *j*
- mdr_i : maintenance distance requirement index for unit *i*

The concept of the first five decision variables is straightforward and depicted in Figure 2. If $fx_{ij} = 1$ (as it is in Figure 2), it follows that units *i* and *j* are completely separated along the *x*-axis and *j* is ahead of *i*. According to Figure 2, $fx_{ji} = 0$ as unit *i* is not ahead of *j*. Also, $fy_{ji} = fy_{ij} = 0$ as the units intersect along the *y* axis.

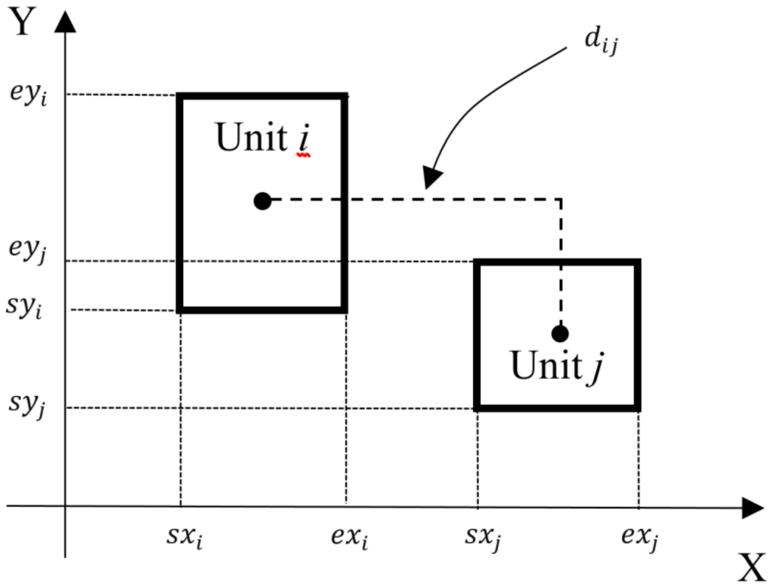

Figure 2. Display of some of the decision variables

If, $x_{ij} = 1$, it follows that in addition to the two units being completely separated and *j* being ahead along *x*, they intersect along the *y* axis. In Figure 2 $x_{ij} = 1$ but $x_{ji} = y_{ij} = y_{ji} = 0$. The *x* and *y* variable is very important in the model as they are the basis of computing accessibility to units for maintenance. Moreover, *x* and *y* variables in combination with *fx* and *fy* make our model novel in comparison with the current literature and provide a suitable basis for the application of metaheuristic frameworks. In other words, metaheuristics are either neighborhood-based (base on local search) or population-based. In the case of the former, the aforementioned binary variables will be suitable for neighborhood structure definition, and in the case of the latter, the variables will help define operators like crossover or mutation.

pdr_{ij} is simply the somehow classical adjacency factor between units i and j that is computed according to min_pdr_{ij}, max_pdr_{ij}, $w\_min\_dist_{ij}$ and $w\_max\_dist_{ij}$ once the locations of the two units are given. mdr_i is obtained according to n_dr_i and n_mopr_i once the locations of all units are given. It reflects the free space around unit *i* that is used for maintenance operations.

3.3 Objective functions

The MINLP model of this research involves three objective functions:

- minimization of the sum of accessibility to units
- minimization of the sum of all pdr_{ij} 's
- minimization of the sum of violation of free maintenance distance requirement around all units

If a door exists in the bottom edge of the location area, $\sum_j y_{ji}$ indicates the number of units that are blocking the access of unit *i* from that door. $\sum_j x_{ji}$, $\sum_j y_{ji}$ and $\sum_j x_{ij}$ computes the same value for unit *i* from the right, top, and left edge respectively. Hence, the accessibility of unit *i* is:

$$\text{Accessibility}_i = min\left((1-dr_1)M + \sum_j x_{ij}, (1-dr_2)M + \sum_j x_{ji}, (1-dr_3)M + \sum_j y_{ij}, (1-dr_4)M + \sum_j y_{ji}\right) \tag{3}$$

where *M* is a sufficiently big number. Notice that if an edge does not have a door, the relevant term is ineffective in Equation 3, and accessibility is not obtained through that edge. The total accessibility index to be minimized can be written as equation 4.

$$Total\ \text{Accessibility} = \sum_i \text{Accessibility}_i \tag{4}$$

The second objective to be minimized is the classic total pairwise distance requirement index which may be expressed as equation 5.

$$Total\ Pairwise\ Distance\ Requirement = \sum_i \sum_j pdr_{ij} \tag{5}$$

The last objective is the minimization of the total maintenance distance requirement index. It is written as equation 6.

$$\text{Maintenance Distance Requirement Index} = \sum_i mdr_i \tag{6}$$

3.4 Constraints

Expressions 7 to 29 constitute the constraints of our model. The combination of these constraints and the three above-mentioned objective functions results in an MINLP model. MINLP models are harder than their pure integer variants, however, the literature of mathematical programming contains many novels and efficient approaches for tackling them (see for example [13]).

$$ex_i = sx_i + lx_i \qquad \forall i \tag{7}$$

$$ey_i = sy_i + ly_i \qquad \forall i \tag{8}$$

$$d_{ij} = \left|sx_i + \frac{lx_i}{2} - sx_j - \frac{lx_j}{2}\right| + \left|sy_i + \frac{ly_i}{2} - sy_j - \frac{ly_j}{2}\right| \qquad \forall i,j \tag{9}$$

$$pdr_{ij} = \begin{cases} w\_min\_dist_{ij}(min\_pdr_{ij} - d_{ij}) & if \;\; d_{ij} < min\_pdr_{ij} \\ w\_max\_dist_{ij}(d_{ij} - max\_pdr_{ij}) & if \;\; d_{ij} > max\_pdr_{ij} \\ 0 & otherwise \end{cases} \qquad \forall i,j \tag{10}$$

$$mdr_i = \begin{cases} n\_mopr_i\left(n\_dr_i - min_{\mathrm{j}}(d_{ij})\right) & if \;\; n\_dr_i > min_{\mathrm{j}}(d_{ij}) \\ 0 & otherwise \end{cases} \qquad \forall i \tag{11}$$

$$ex_i \le sx_j + M(1 - fx_{ij}) \qquad \forall i,j \tag{12}$$

$$\frac{1}{M} + sx_j \le ex_i + Mfx_{ij} \qquad \forall i,j \tag{13}$$

$$ey_i \le sy_j + M(1 - fy_{ij}) \qquad \forall i,j \tag{14}$$

$$\frac{1}{M} + sy_j \le ey_i + Mfy_{ij} \qquad \forall i,j \tag{15}$$

$$fx_{ij} + fx_{ji} + fy_{ij} + fy_{ji} \ge 1 \qquad i > j \tag{16}$$

$$x_{ij} \ge fx_{ij} - fy_{ij} - fy_{ji} \qquad \forall i,j \tag{17}$$

$$x_{ij} \le fx_{ij} \qquad \forall i,j \tag{18}$$

$$x_{ij} \le 1 - fy_{ij} \qquad \forall i,j \tag{19}$$

$$x_{ij} \le 1 - fy_{ji} \qquad \forall i,j \tag{20}$$

$$y_{ij} \ge fy_{ij} - fx_{ij} - fx_{ji} \qquad \forall i,j \tag{21}$$

$$y_{ij} \le fy_{ij} \qquad \forall i,j \tag{22}$$

$$y_{ij} \le 1 - fx_{ij} \qquad \forall i,j \tag{23}$$

$$y_{ij} \le 1 - fx_{ji} \qquad \forall i,j \tag{24}$$

$$0 \le sx_i \le Tlx \qquad \forall i \tag{25}$$

$$0 \le sy_i \le Tly \qquad \forall i \tag{26}$$

$$0 \le ex_i \le Tlx \qquad \forall i \tag{27}$$

$$0 \le ey_i \le Tly \qquad \forall i \tag{28}$$

$$x_{ij}, y_{ij}, z_{ij}, fx_{ij}, fy_{ij}, fz_{ij} \in \{0,1\} \qquad \forall i,j \tag{29}$$

Equations 7 and 8 are definitions of ending points of units. Equation 9 defines the rectilinear distance between center points of units. Equation 10 is the definition of pdr_{ij}. If units i and j are closer than min_pdr_{ij}, a penalty is incurred. A similar penalty is considered if units are too far away. $min_{\mathrm{j}}(d_{ij})$ is the distance of the closest unit to unit i. According to Equation 11, if $n\_dr_i > min_{\mathrm{j}}(d_{ij})$, the free maintenance space around unit i is violated and a proportional penalty applies. This approach is different from Equation 1 that was mentioned earlier. If $fx_{ij} = 1$, $ex_i \le sx_j$ should hold. On the other hand, if $fx_{ij} = 0$, $sx_j < ex_i$ should hold. Notice that the latter is a strict inequality. This situation is modeled by the big M technique via expressions 12 and 13. Expressions 14 and 15 demonstrate the same idea along the y-axis. Expression 16 is our novel method of ensuring that no two units occupy the same space. Since the expression is symmetric, it only should be written once for each pair ij. Expression 17 ensures that If $x_{ij} = 1$ then fx_{ij} is 1 and fy_{ij} and fy_{ji} are zero. Notice that if one of the three latter equalities are violated, Equation 17 becomes redundant. If so, x_{ij} must be zero. This is guaranteed by expressions 18-20. Expressions 21-24 demonstrate the same idea for y_{ij}. Finally, domains of variables are defined by expressions 25 to 29.

4. Numerical experiments

In order to demonstrate the model validity and analyze the effect of maintenance orientation of the model of this research, 30 test problems are randomly created and solved. The number of units i.e. n is considered 5, 8, and 12. Solving larger test problems is time-consuming since the model is MINLP. In each run, one of the objective functions is considered. The other two objectives are also calculated and reported, though not optimized. The location area is considered to be a single door ($dr_1 = 1$) $a \times a$ square where $a = 5, 10\ and\ 18$ for $n = 5, 8\ and\ 12$ respectively. Two scenarios are considered regarding the congestion of the problems. In scenario 1, a 40% congestion level is considered which entails that the sum of areas of units is roughly 40% of the area of location square. In scenario 2, the congestion ratio is roughly 70%. The width and length of units are created randomly so that the two congestion ratios roughly stand. For simplicity, weight factors in the model (*w_min_dist, w_max_dist, n_mopr*) are all set to one. On average, the minimum Manhattan distance between two units is $\overline{lx} + \overline{ly}$ where the bar symbol stands for the average. Hence, n_dr_i is set to $\left(\overline{lx} + \overline{ly}\right) \times 1.15$ which entails a 15% extra distance for maintenance operations of units.

According to Equation 3, 6 and the content of section 2, objective functions 1 and 3 are clearly maintenance oriented. However, objective 2 entails units not being too close, which is maintenance oriented, and not being too far, which relates to the classical adjacency nature of FLP and mirrors the cost of material handling. Hence, objective function 2 possesses two orientations: maintenance and material handling. However, if $min\_pdr_{ij} = max\_pdr_{ij} = 0$ for all values of i and j, the cost of units being too close (a maintenance cost) is omitted and objective function 2 will become pure in the sense that it only represents material handling costs. In this way, objective function 2 will represent the classical FLP while objective 1 and 3 will do the same for the maintenance-oriented FLP model of this research. All in all, min_pdr_{ij} and max_pdr_{ij} are set to zero to create a basis for comparison of classical FLP with the maintenance-oriented model by comparing objective function 2 with objective functions 1 and 3.

Following notations are used for each test problem:

Table 2. Results of 30 randomly created test problems solved by the MINLP model of this research via Lingo 18.0

N	Congestion ratio	Test problem no.	z_1 is optimized			z_2 is optimized			z_3 is optimized			Sub-optimality ratios			
			z_1^*	z_{21}	z_{31}	z_{12}	z_2^*	z_{32}	z_{13}	z_{23}	z_3^*	θ_{21}	θ_{12}	θ_{13}	θ_{23}
5	40%	1	2	132	18.75	3	104	24.25	4	160	8.25	27%	50%	194%	54%
		2	2	168	0.84	7	76	19.55	3	157	0.00	121%	250%	-	107%
		3	2	160	0.00	5	76	19.20	2	160	0.00	111%	150%	-	111%
		4	3	160	9.00	4	106	23.75	3	160	9.00	51%	33%	164%	51%
		5	2	132	14.00	6	88	20.50	4	170	0.00	50%	200%	-	94%
	70%	6	4	170	0.00	5	116	24.35	4	170	0.00	47%	25%	-	47%
		7	3	129	25.75	4	126	26.50	4	142	21.00	2%	33%	26%	13%
		8	3	143	25.90	3	124	28.65	3	144	20.65	15%	0%	39%	16%
		9	4	142	24.50	5	122	27.00	5	146	19.50	16%	25%	38%	20%
		10	4	136	27.80	4	128	28.30	4	148	23.30	6%	0%	21%	16%
8	40%	11	10	384	14.62	16	249	25.70	10	422	7.49	54%	60%	243%	70%
		12	5	385	14.85	13	273	26.85	9	419	13.68	41%	160%	96%	53%
		13	5	400	19.80	8	277	28.80	8	401	11.30	44%	60%	155%	45%
		14	5	384	10.88	16	242	22.40	7	388	8.40	59%	220%	167%	60%
		15	4	401	20.35	10	267	25.85	7	429	9.35	50%	150%	176%	61%
	70%	16	7	391	28.65	11	309	34.65	9	415	25.15	27%	57%	38%	34%
		17	8	345	22.95	14	239	33.95	8	427	16.45	44%	75%	106%	79%
		18	9	500	22.20	13	331	37.20	10	546	19.80	51%	44%	88%	65%
		19	6	452	16.70	17	286	28.85	8	509	14.15	58%	183%	104%	78%
		20	8	414	26.15	11	314	49.75	9	506	23.55	32%	38%	111%	61%
12	40%	21	8	1949	32.95	21	1333	57.65	14	2240	27.45	46%	163%	110%	68%
		22	9	2096	57.95	28	1504	106.25	18	2364	48.30	39%	211%	120%	57%
		23	11	1859	40.50	25	1175	72.25	20	2172	33.75	58%	127%	114%	85%
		24	9	2294	61.35	30	1612	107.95	11	2442	51.15	42%	233%	111%	51%
		25	8	2138	35.55	23	1539	75.45	12	2364	29.65	39%	188%	121%	54%
	70%	26	13	1521	69.80	31	1234	85.50	26	1566	58.65	23%	138%	46%	27%
		27	12	1450	65.70	33	1036	164.25	15	1533	64.15	40%	175%	156%	48%
		28	13	1930	64.55	25	1266	95.00	18	1911	39.35	53%	92%	116%	51%
		29	14	1702	75.70	16	1205	95.50	14	1820	48.25	41%	14%	78%	51%
		30	11	1759	48.40	18	1162	109.50	17	1754	49.50	51%	64%	101%	51%

z_{ij}: = value of the i^{th} objective function (accessibility, pairwise distance requirement, and maintenance distance requirement index) when the j^{th} objective is optimized

z_i^*: the optimal value of the i^{th} objective function.

θ_{ij}: the sub-optimality ratio of *i*th objective as a result of optimizing *j*th objective i.e. $\frac{|z_j^* - z_{ij}|}{z_{ij}}$

All thirty test problems were implemented in Lingo 18.0. A maximum runtime limit of 30 minutes was considered after which the best solution was reported. If a test problem was infeasible, it was simply replaced. Table 2 contains a summary of the results (objective function values). For the sake of brevity, the [near] optimal values of sx_i, sy_i, ex_i and ey_i for all i's are not reported here but are available to interested readers.

According to Table 2, the average values of θ_{21}, θ_{12}, θ_{13} and θ_{23} are 45%, 107%, 109% and 56%. θ_{21} and θ_{23} are less than (nearly half of) θ_{12} and θ_{13} which means optimizing the maintenance feature of the model has a less adverse effect on the material handling costs than vice versa. In other words, while minimization of material handling costs almost doubles the maintenance costs, minimization of maintenance costs only causes a near 50% increase in material handling costs.

A rather interesting observation is the effect of *n* on the sub-optimality ratios. $(\theta_{21}, \theta_{23})$ for *n*=5, 8, and 12 are (45%,53%), (46%,61%) and (48%,59%). In other words, $(\theta_{21}, \theta_{23})$ does not seem to be much sensitive to n. One can conclude that optimizing each of the maintenance objectives causes roughly a 50% deviation from optimality in material handling costs regardless of the number of units to be located. On the other hand, $(\theta_{12}, \theta_{13})$ show a positive relationship with *n* ((77%, 48%), (105%,128%) and (150%,131%)) stating that for larger problems, optimizing the material handling costs results in larger sacrifices in maintenance costs.

Congestion ratios seem to affect the outcome as well. Average values of θ_{21}, θ_{12}, θ_{13} and θ_{23} are 56%, 150%, 150% and 68% when congestion ratio is 40%. These values change to 34%, 64%, 81% and 44% for congestion ratio of 70%. It is evident that when the location area is crowded, optimizing one objective function needs more deviation from optimality in other objectives. In other words and as expected, objective functions are less sensitive to each other in location areas with more free space.

5. Conclusions

In this research, a mixed-integer nonlinear model for facility layout problem was developed. The model incorporated some new elements regarding the maintenance of units to be located. Classic facility layout problem is mostly focused on material handling costs. In the model of this research, two new objective functions were developed that focused on the accessibility of units for emergent maintenance operations and free space around units for performing regular maintenance actions. The structure of the proposed model possessed some novel features in comparison with the literature. The model was analyzed and validated via solving some simulated random test problems. Results revealed that if material handling costs were minimized, the two maintenance related objectives would deviate approximately 100% of their optimal values. Moreover, if each of the maintenance related objectives were optimized, material handling costs would deviate around 50% from their optimal value. Results also conveyed that a more congested and dense production environment would increase the above numbers in general. The MILNP nature and computational complexity of the model of this research is a pitfall. This characteristic is rooted in the definition of the distance (Manhattan) and objective functions. Ergo, future studies can be centered on the development of heuristic, metaheuristic, and other approximation techniques, which create the ability to tackle larger problems.

6. References

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