MULTI OBJECTIVE ROBUST OPTIMIZATION MODEL FOR FACILITY LAYOUT DESIGN UNDER DEMAND UNCERTAINTY

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ABSTRACT

This paper discusses the development of a multi-objective robust optimization model for facility layout design in the manufacturing systems. This proposed model considers the uncertainty of demand for each type of product. The facility layout design has three objectives, namely minimizing the expected total material handling cost, maximizing the total adjacency value between departments which is the functional relationship and adjacency requirements, and maximizing the utilization of the total area available. In addition, this proposed model considered the production process flow of each type of products, the value of adjacency between departments and the demand uncertainty for each type of product, such that the resulting facility layout is robust. The demand uncertainty for each type of products were expressed in the form of discrete scenarios with certain probabilities according to historical demand data. The demand uncertainty for each type of products has an impact on the uncertainty of the frequency of material movement between departments, which would affect the determination of the optimal position of one department against other departments. The proposed model of multi objective robust optimization for facility layout design had been solved using Gurobi Optimization - Python programming. Numerical experiment had been presented to show the results of applying the proposed model to assist facility planning managers in obtaining an efficient facility layout.

Keywords: Multi objective robust optimization model, unequal area facility layout design, demand uncertainty.

1. INTRODUCTION

Facility layout planning is an important factor in the manufacturing industry, because around 20% -50% of the operational costs in a manufacturing system depend on facility planning and material handling design. Material handling cost efficiency from an optimal facility layout will result in operational cost savings of approximately 10% -20% (Tompkins et al., 2010). In the facility layout planning, it is necessary to consider the process flow, the dimensions of department length and width, and the area required for each department. In addition, the relationship between departments and the characteristics of each department will have an effect on the effective position of each department in manufacturing system.

So far, few researches have been done on the optimization model of facility layout planning that took into account the uncertainty of demand for each type of product. The uncertainty of product demand has an impact on the uncertainty of material transfer frequency between departments, which affects the effective positioning of the department as an element in material handling costs.

Therefore, this paper will propose a multi objective robust optimization model for unequal area facility layout planning by considering the uncertainty of product demand.

The following sections of this paper is organized as follows. In Section 2, we will discuss the literature review related to the design of the facility layout optimization model, followed by Section 3 discussing the description of the facility layout problems to be solved. The development of the multi-objective optimization model is described in detail in Section 4. Section 5 presents a numerical example and a discussion of the results of applying the proposed model. Finally, conclusions and suggestions for further research are provided in Section 6.

2. RELATED WORK

In order to reach efficient production and service system, companies should not only make the right production planning and policies, but also must have a well-planned and well-designed facility layout plan (Zha *et al.*, 2017). Facility Layout Problem (FLP) is one of the most critical issues in industrial management and engineering. Various approaches have emerged to achieve optimal solutions (Guan *et al.*, 2019). Facility layout problems are also known to be complex with a variety of considerations to be taken into account (Drira, Pierreval and Hajri-Gabouj, 2006). One of the important considerations in facility layout design is to determine the flow pattern through the system for materials, parts, and the work-in-process (Drira, Pierreval *et al*. 2007). (Hosseini-Nasab *et al.*, 2018) divides FLP into four groups based on layout evaluation, workshop characteristics, problem formulation, and approaches.

The material flow is one of the criteria commonly used to evaluate flow in a facility. (Chhajed, Montreuil and Lowe, 1992) have developed a material flow design network model called the *Shortest rectilinear flow network problem (shortest r-flow network).* The objective is to minimize the cost of a network flow in facility layout. Its assuming free flow, an unidirectional, and the rectilinear travel norm. (Saraswat, Venkatadri and Castillo, 2015) presented a framework for multi-objective facility layout design based on flow–distance, average work-in-process, and the number of required material handling devices. (Chiang, Kouvelis and Urban, 2006) presented a multi-objective facility layout design considering the workflow interference between interconnected departments. As discussed in Tompkins *et.al*. (2010) about minimizing the interruptions that produce congestion and unwanted intersections.

Various studies also considered the uncertain demand patterns. According to (Raman *et al.*, 2007) based on the demand characteristics, the facilities layout problem can be categorized into two groups, that is the single period layout, when the demand is almost constant, and the flexible or robust layout, when there is a variation in demand. (Zha *et al.*, 2017) proposed a method to solve FLP in manufacturing system under uncertainty demand. (Xiao *et al.*, 2019) proposed a hybrid robust optimization model for unequal-area dynamic facility layout problem by considering the location of pick-up and drop-off points. (Vitayasak, Pongcharoen and Hicks, 2019) proposed a robust layout design tool for machine layout in manufacturing systems that minimize the material flow distance using a Genetic Algorithm, by considering uncertainty demand and machine maintenance. The results show the result show a shorter material flow.

The travel frequency determines the relationship factor between departments. So, the departments with high traffic should be placed closer to each other (Tongur, Hacibeyoglu and Ulker, 2020). Research in service industry was done by (Tongur, Hacibeyoglu and Ulker, 2020) who solved a big-scale hospital facility layout problem using meta-heuristic algorithms by formulated the objective function according to the physical structure of the hospital, number of polyclinics, and the monthly average number of inpatients and number of consultations between each department.

The adjacency value between departments represents a functional relationship and corresponds to the adjacency requirement (Liu *et al.*, 2018), as shown in Table 1 and Table 2.

Table 1. Adjacency values corresponding to adjacency requirement

Adjacency requirement	Adjacency value	Relationship
A	5	Extremely desirable
E	4	Very desirable
I	3	Desirable
O	2	Indifferent
U	1	Unimportant
X	0	Undesirable

Table 2. Range of adjacency factor

Relationship condition	Adjacency factor
$0 < d_{ij} \leq d_{max}/6$	1.0
$d_{max}/6 < d_{ij} \leq d_{max}/3$	0.8
$d_{max}/3 < d_{ij} \leq d_{max}/2$	0.6
$d_{max}/2 < d_{ij} \leq 2d_{max}/3$	0.4
$2d_{max}/3 < d_{ij} \leq 5d_{max}/6$	0.2
$5d_{max}/6 < d_{ij} \leq d_{max}$	0

3. PROBLEM STATEMENT

In this paper, a multi objective robust optimization model for unequal area facility layout problems was developed by considering the static layout plan and interrelated between departments. This facility layout plan might be applied to various manufacturing industries under uncertain demand. Each department has rectangular in shape with two possible orientations, namely in horizontal or vertical direction relatively to the x-axis or y-axis. The distance between departments is measured from the centroid of each department according to the Manhattan distance formula and among departments can have a minimum aisle distance. There are three objectives of this facility layout planning which are to minimize expected total material handling costs, to maximize total adjacency values and to maximize total area utilization. The development of a multi objective robust optimization model will be explained in detail in the following section.

4. MODEL DEVELOPMENT

The development of a multi objective robust optimization model for unequal area facility layout problems is carried out by considering demand uncertainty for each type of product, the production process flow, the characteristics of each department, and the inter-departmental relationship which is stated in the adjacency factor between departments.

Indices:

i, j : set of departments
k : set of adjacent functions
p : set of product types
s : set of discrete scenarios

Model Parameters:

p_s : probability of scenario s
C_{ij} : cost of moving material per unit distance from department i to department j
AV_{ij} : adjacent value of department i to department j
L : length of available area
W : width of available area
D_{ps} : number of demand for product p in scenario s
u_{ijp} : unit load from department i to department j for product p
l_i^l : minimum length of department i
l_i^u : maximum length of department i
w_i^l : minimum width of department i
w_i^u : maximum width of department i
a_{ij}^x : minimum width of aisle from department i to department j in x-axis direction
a_{ij}^y : minimum width of aisle from department i to department j in y-axis direction
M : a significant positive number

Decision Variables:

x_i : centroid of department i in x-axis direction
y_i : centroid of department i in y-axis direction
l_i : length of department i
w_i : width of department i
af_{ij} : adjacent function between department i and department j
d_{ij} : Manhattan distance between the centroid of department i and centroid of department j
d_{ij}^x : distance between the centroid of department i to the centroid of department j in x-axis direction
d_{ij}^y : distance between the centroid of department i to the centroid of department j in y-axis direction
z_i : binary variables; 1 if the length of the department i unidirectional with the x-axis, 0 if the length of the department i unidirectional with the y-axis
v_{ijk} : binary variables; 1 if d_{ij} within range k and has *adjacent function* af_{ij}
δ_{ij}^x : binary variables; 1 if the position of department i is on the left side of department j, and 0 otherwise
δ_{ij}^y : binary variables; 1 if the position of department i is at the bottom side of department j, and 0 otherwise
d_{max} : the maximum distance between departments
f_{ijs} : total frequency of movement from department i to department j in scenario s.

Objective Functions:

$$Min.TC = \sum_{s \in S} p_s \{C_s(d_{ij}) + \lambda | C_s(d_{ij}) - \sum_{s' \in S} p_{s'} C_s(d_{ij}) + 2\theta_s | \} \quad (1)$$
$$Max.TAV = \sum_{i \in N} \sum_{j \in N} AV_{ij}.af_{ij} \quad (2)$$
$$Max.UR = \frac{\sum_{i \in N} l_i.w_i}{L.W} \quad (3)$$

Constraints:

$$C_s(d_{ij}) = \sum_{i\in N}\sum_{j\in N}\sum_{s\in S} p_s.C_{ij}.f_{ijs}.d_{ij} \tag{4}$$

$$C_s(d_{ij}) - \sum_{s'\in S} p_{s'} C_s(d_{ij}) + \theta_s \ge 0 \qquad \forall s \tag{5}$$

$$f_{ijs} = \left\lceil \frac{D_{ps}}{u_{ijp}} \right\rceil \qquad \forall i,j,s \tag{6}$$

$$d_{ij} = |x_i - x_j| + |y_i - y_j| \qquad \forall i,j \tag{7}$$

$$l_i^l \le l_i \le l_i^u \qquad \forall i \tag{8}$$

$$w_i^l \le w_i \le w_i^u \qquad \forall i \tag{9}$$

$$\frac{1}{2}[l_i z_i + w_i(1-z_i)] \le x_i \le L - \frac{1}{2}[l_i z_i + w_i(1-z_i)] \qquad \forall i \tag{10}$$

$$\frac{1}{2}[w_i z_i + l_i(1-z_i)] \le y_i \le W - \frac{1}{2}[w_i z_i + l_i(1-z_i)] \qquad \forall i \tag{11}$$

$$x_i + \frac{1}{2}[l_i z_i + w_i(1-z_i)] + a_{ij} \le x_j - \frac{1}{2}[l_j z_j + w_j(1-z_j)] + M(1-\delta^x_{ij}) \qquad \forall i,j \tag{12}$$

$$y_i + \frac{1}{2}[w_i z_i + l_i(1-z_i)] + a_{ij} \le y_j - \frac{1}{2}[w_j z_j + l_j(1-z_j)] + M(1-\delta^y_{ij}) \qquad \forall i,j \tag{13}$$

$$\delta^x_{ij} + \delta^x_{ji} + \delta^y_{ij} + \delta^y_{ji} \ge 1 \qquad \forall i,j \tag{14}$$

$$d_{ij} \le \frac{d_{max}}{6} v_{ij1} + \frac{d_{max}}{3} v_{ij2} + \frac{d_{max}}{2} v_{ij3} + \frac{2.d_{max}}{3} v_{ij4} + \frac{5.d_{max}}{6} v_{ij5} + d_{max} v_{ij6} \qquad \forall i,j \tag{15}$$

$$af_{ij} = v_{ij1} + 0.8v_{ij2} + 0.6v_{ij3} + 0.4v_{ij4} + 0.2v_{ij5} \qquad \forall i,j \tag{16}$$

$$\sum_{k=1}^{6} v_{ijk} = 1 \qquad \forall i,j \tag{17}$$

$$d_{max} = L - \min_{i\in N} x_i + W - \min_{i\in N} y_i \tag{18}$$

Decision variables domain:

$$x_i, y_i, l_i, w_i \ge 0 \qquad \forall i \tag{19}$$

$$af_{ij}, d_{ij}, d^x_{ij}, d^y_{ij} \ge 0 \qquad \forall i,j \tag{20}$$

$$z_i \in \{0,1\} \qquad \forall i \tag{21}$$

$$\theta_s \ge 0 \qquad \forall s \tag{22}$$

$$v_{ijk} \in \{0,1\} \qquad \forall i,j,k \tag{23}$$

$$\delta^x_{ij}, \delta^y_{ij} \in \{0,1\} \qquad \forall i,j \tag{24}$$

$$f_{ijs} \ge 0 \,\&\, integer \qquad \forall i,j,s \tag{25}$$

The first objective function (1) is to minimize the expected total cost of moving between departments per period. The second objective function (2) is to maximize the total adjacency values between departments based on relationships and distances between departments. The third objective function (3) is to maximize the utilization of the used area for all departments to the available area. Formula (4) is the expected total cost of material transfer between departments for all possible quantities of demand for each type of product in each scenario. Constraints (5) is used for linearizing the absolute value of the difference between the expected total cost of moving between departments and the expected total cost of material movement under a given scenario. Formula (6) shows the frequency of transfers between departments for each scenario based on the number of requests for each product type and unit load between departments for each type of product in each scenario. Formula (7) is to determine the Manhattan distance between departments which is calculated from the centroid of each department. The constraints (8) and (9) are the length and width ranges of each department. The constraints (10) and (11) define the midpoint positions of each department in the x and y-axis directions. Constraints (12) - (14) shows the position of each department against the other departments in the x and y-axis directions without overlapping in both dimensions. Constraint (15)

- (17) is the relationship of the position between departments and the distance between departments according to the frequency of material movement and the characteristics of each department. Formula (18) defines the maximum distance between departments and domains for each decision variable expressed in constraints (19) - (25).

The absolute function in Manhattan distance between centroid of departments can be linearized with a series of constraints as stated on constraints (23) - (28).

$$d_{ij} = d^x_{ij} + d^y_{ij} \qquad \forall i,j \tag{26}$$

where:

$$d^x_{ij} \geq x_i - x_j \qquad \forall i,j \tag{27}$$

$$d^x_{ij} \geq x_j - x_i \qquad \forall i,j \tag{28}$$

$$d^y_{ij} \geq y_i - y_j \qquad \forall i,j \tag{29}$$

$$d^y_{ij} \geq y_j - y_i \qquad \forall i,j \tag{30}$$

$$d^x_{ij}, d^x_{ij} \geq 0 \qquad \forall i,j \tag{31}$$

In the next section, we will discuss the application of the multi objective robust optimization model for determining the optimal solution for the unequal area - facility layout problem.

5. DISCUSSION

A multi-objective optimization model to determine the unequal area of facility layout problem by considering the uncertainty of multi-product demand is applied to the following numerical experiment. The dimensions of the available area are L = 55 units, W = 40 units, the aisle width between departments in the x-axis and y-axis directions is 3 units.

The sequence of the production process for each type of product through several required departments is shown in Table 3.

Table 3. The sequence of the production process for each type of product

Sequence	Dept 1	Dept 2	Dept 3	Dept 4	Dept 5	Dept 6	Dept 7	Dept 8
Product A	1	2	3			4		5
Product B	1		2	3			4	
Product C	1			2	3		4	5
Product D		1	2			3		4
Product E	1	2			3		4	
Product F		1			2	3		4
Product G		1	2			3		4
Product H	1		2	3	4		5	
Product I	1	2		3			4	
Product J		1		2		3	4	5
Product K	1	2			3	4		5
Product L	1		2		3		4	5

Table 4. and Table 5 show the number of demand for each type of product in each scenario with the same probability value for each scenario and the number of unit load for each type of product that moves between departments.

Table 4. Number of demand for each type of product in each scenario

Demand	Scen 1	Scen 2	Scen 3	Scen 4	Scen 5	Scen 6	Scen 7	Scen 8	Scen 9	Scen 10
Product A	2830	1170	2270	1080	2960	1840	2270	1230	1370	2250
Product B	3180	3810	3230	2600	3600	3730	2660	2060	3340	2880
Product C	1830	1420	1530	1050	1670	1890	1790	1400	1120	1080
Product D	4400	4980	4730	3810	3090	4280	4930	4740	3460	4960
Product E	2630	2580	2050	2730	2030	2930	2690	2110	2440	2010
Product F	2680	1040	1830	1740	1000	1170	1480	1050	1240	1230
Product G	3450	3070	3370	3590	3050	5000	4410	3270	3180	4870
Product H	1440	3890	2750	1940	3880	1730	1060	1010	1340	2930
Product I	2950	3650	3880	3360	3240	3360	2950	3130	2850	3560
Product J	3990	3950	3210	2440	4170	3190	4780	2670	2400	3500
Product K	1940	3100	2940	1680	2890	3280	3740	3730	2210	1570
Product L	2130	2510	4020	4200	2280	2480	3530	4870	3210	4540

Table 5. Number of unit load for each type of product that moves between departments

Unit Load	Dept 1	Dept 2	Dept 3	Dept 4	Dept 5	Dept 6	Dept 7	Dept 8
Product A		25	25			40		50
Product B			30	30			40	
Product C				25	25		30	40
Product D			30			30		50
Product E		20			30		40	
Product F					30	40		50
Product G			20			30		40
Product H			30	30	40		50	
Product I		25		30			40	
Product J				25		30	40	50
Product K		30			30	40		50
Product L			30		30		40	40

Dimensional range of length and width of each department and the material handling cost per unit between departments are shown in Table 6 and Table 7 as follow.

Table 6. Dimensional range of length and width of each department.

Dept	l_i^l	l_i^u	w_i^l	w_i^u
Dept 1	15	23	8	16
Dept 2	13	22	10	15
Dept 3	11	16	5	14
Dept 4	16	23	8	17
Dept 5	15	24	10	17
Dept 6	17	22	6	12
Dept 7	13	18	9	16

Dept	l_i^l	l_i^u	w_i^l	w_i^u
Dept 8	16	25	9	16

Table 7. Material handling cost per unit between departements

C_{ij}	Dept 1	Dept 2	Dept 3	Dept 4	Dept 5	Dept 6	Dept 7	Dept 8
Dept 1	0	19	19	10	17	10	14	20
Dept 2	19	0	14	19	16	16	14	19
Dept 3	19	14	0	11	17	15	10	15
Dept 4	10	19	11	0	19	12	15	10
Dept 5	17	16	17	19	0	16	12	20
Dept 6	10	16	15	12	16	0	15	13
Dept 7	14	14	10	15	12	15	0	10
Dept 8	20	19	15	10	20	13	10	0

The results of the frequency of material movement between departments for scenario 1 based on the demand for each type of product, unit load between departments, and the sequence of processes at the department for each type of product are shown in Table 8.

Table 8. Example of the total frequency of transfers between departments for Scenario 1

f_{ij1}		Dept 1	Dept 2	Dept 3	Dept 4	Dept 5	Dept 6	Dept 7	Dept 8
Scen 1	Dept 1	0	429	225	74	0	0	0	0
	Dept 2	0	0	434	259	243	0	0	0
	Dept 3	0	0	0	154	71	333	0	0
	Dept 4	0	0	0	0	110	133	154	0
	Dept 5	0	0	0	0	0	116	210	0
	Dept 6	0	0	0	0	0	0	100	268
	Dept 7	0	0	0	0	0	0	0	237
	Dept 8	0	0	0	0	0	0	0	0

Based on all available information and characteristic data of each department, the multi-objective robust optimization model was solved by using Gurobi Optimization - Python programming and obtained the optimal solution for the centroid position and orientation of each department as shown in Table 9.

The optimal solution provides the minimum expected total cost of $ 1,081,164, the maximum total adjacency value of 139.2 and the maximum area utilization ratio of 47.27%.

Table 9. The optimal solution for each of department centroid position and orientation

Dept	l_i	w_i	x_i	y_i	z_i
Dept 1	15	9	47	6	1
Dept 2	13	11	47	19	1
Dept 3	11	5	35	19	0
Dept 4	17	9	46	32	1
Dept 5	15	11	27	33	1

Dept	l_i	w_i	x_i	y_i	z_i
Dept 6	17	7	21	19	1
Dept 7	13	9	12	33	0
Dept 8	17	9	5	15	0

Based on the optimal position for each department in the facility layout, we got the Manhattan distances and the adjacency factor values between departments as shown in Table 10 and Table 11, and the floor plan of the optimal facility layout in Figure 1.

Table 10. Manhattan distance between departments

d_{ij}	Dept 1	Dept 2	Dept 3	Dept 4	Dept 5	Dept 6	Dept 7	Dept 8
Dept 1	0	13	25	27	80	39	62	80
Dept 2	13	0	12	14	34	26	49	46
Dept 3	25	12	0	24	22	14	37	34
Dept 4	27	14	24	0	20	38	35	58
Dept 5	80	34	22	20	0	20	15	80
Dept 6	39	26	14	38	20	0	23	20
Dept 7	62	49	37	35	15	23	0	25
Dept 8	80	46	34	58	80	20	25	0

Table 11. Adjacency factor between departments

af_{ij}	Dept 1	Dept 2	Dept 3	Dept 4	Dept 5	Dept 6	Dept 7	Dept 8
Dept 1	1	1	0,8	0,8	0	0,6	0,2	0
Dept 2	1	1	1	1	0,6	0,8	0,4	0,4
Dept 3	0,8	1	1	0,8	0,8	1	0,6	0,6
Dept 4	0,8	1	0,8	1	0,8	0,6	0,6	0,2
Dept 5	0	0,6	0,8	0,8	1	0,8	0,8	0
Dept 6	0,6	0,8	1	0,6	0,8	1	0,8	0,8
Dept 7	0,2	0,4	0,6	0,6	0,8	0,8	1	0,8
Dept 8	0	0,4	0,6	0,2	0	0,8	0,8	1

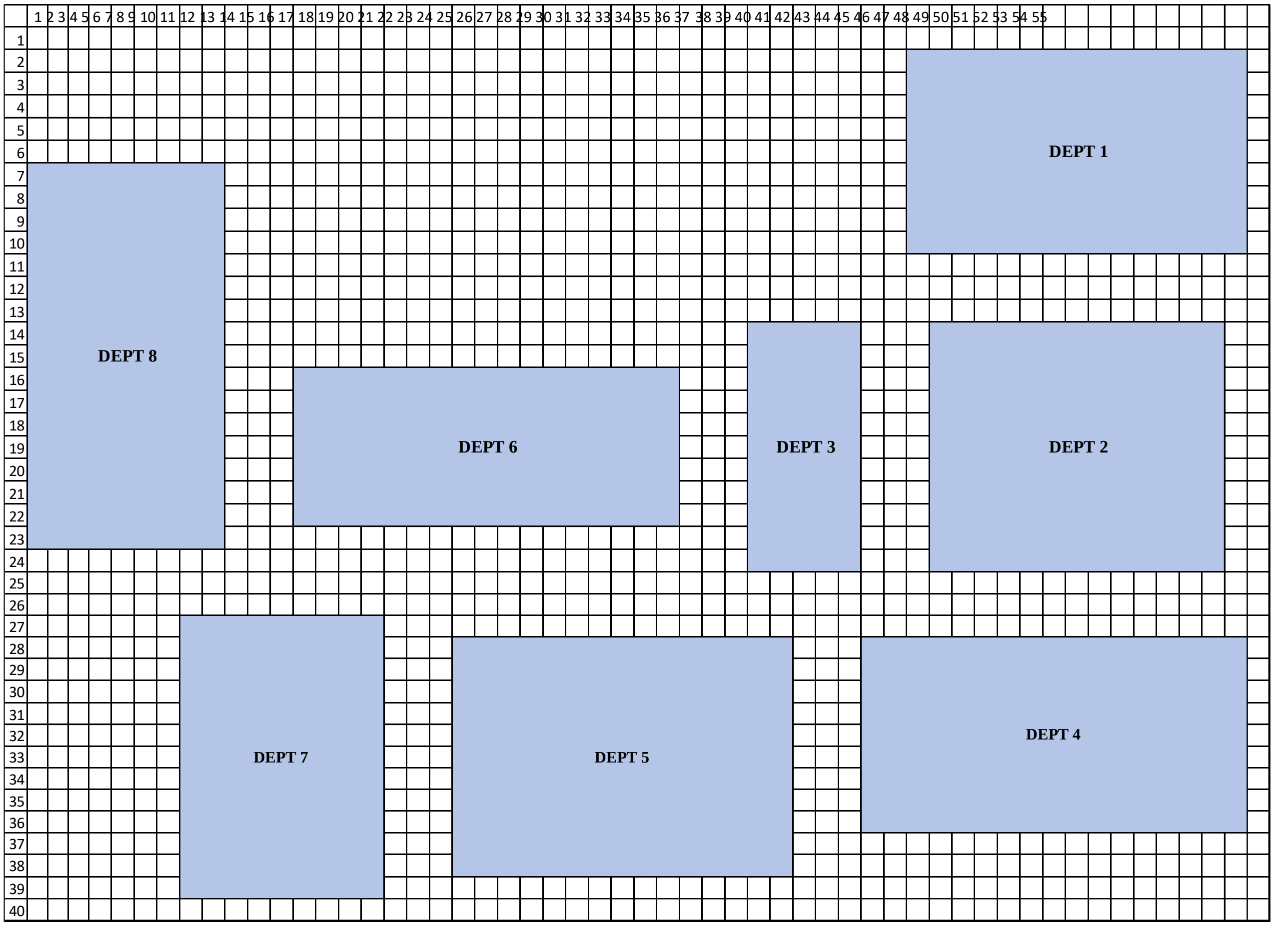

Figure 1. Facility layout in floor plan.

6. CONCLUSIONS

This paper has developed a multi-objective robust optimization model for unequal area facility layout planning by taking into account the uncertainty of demand for each type of product. The uncertainty of product demand will affect the frequency of movement between related departments in the flow of the production process. There are three objectives to be achieved from the facility layout optimization model, namely minimizing the total material handling cost, maximizing total adjacency values and maximizing the area utilization ratio.

In this paper, the solution method for the proposed optimization model had used an exact method which resulted in a long running time to obtain an optimal solution, since facility layout planning is included in the NP-Hard problem category of combinatorial optimization. Moreover, for further research, a heuristics or meta-heuristics solution methods can be developed to be more efficient runtime with nearly optimal solutions.

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