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DECISION MAKING IN MULTI-OBJECTIVE FACILITY LAYOUT DESIGN SELECTION PROBLEM

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ABSTRACT

This paper presents the development of heuristics for determining a common linear machine sequence for multi-products with different operation sequences and facilities with a limited number of duplicate machine types available for a specific job. The final linear machine sequence is obtained by three different methods: (i) Product sequence based on descending order of flow distances, (ii) Product sequence based on descending order of product due date, and (iii) Product sequence based on random selection. This work aims to compare the effectiveness of the three approaches based on the results of (a) minimum total flow distance traveled by products, (b) minimum number of machines in the final linear sequence, and (c) minimum total investment cost of the machines in the final sequence. It is assumed that the product flow runs only in the forward direction, either via in-sequence or bypass movement. This work demonstrates the effectiveness of the proposed heuristics by solving a typical layout design problem taken from the literature and several randomly generated problems. The results of three different approaches are compared, and it provides practical support in making decisions while solving the problems inherent in multi-objective facility layout design.

Keywords: *Facility Layout, Linear Sequencing, Heuristics, Flow Distance and Due date*

1. Introduction

A general facility layout is an integration of the physical arrangement of machines, materials, departments, workstations, storage areas, and common areas within an existing or proposed facility for processing the multi-products in the most efficient manner. Layout decisions significantly affect how efficiently workers can do their jobs; how fast goods can be produced; how difficult it is to automate a system; and how responsive the system can be to changes in product or service design, product mix, and demand volume. In addition, efficient layout design may contribute to reductions in production cycles, idle times, and numbers of bottlenecks or material handling times while simultaneously contributing to an increase in production output, with obvious implications on productivity.

Multi-product flow lines enable the simultaneous production of different commodities in a single flow line setup, thereby maximizing the manufacturing process [1]. Machine layout or flow line design involves determining the relative positions of machines (i.e., the layout) in facilities where a given product is manufactured. Assembly cell layouts can be classified as follows: (a) unidirectional network loop layout, (b) linear single-row layout, (c) linear double-row layout, (d) circular layout, and (e) cluster layout [2,3]. A linear machine sequence is the most commonly used in production systems because of its simplicity and efficient flow structure [4,5] and because it lends itself to the arrangement of machines in a variety of flow configurations, such as a straight line, U-shaped line, serpentine line, or loop for a conveyor or automated guided vehicle system [6]. It presents the advantages of shorter flow distance, easier control of the production process, and easier material handling. It is also the most prevalent layout form in cellular manufacturing systems and flexible manufacturing systems (FMSs) [5,7]. Therefore, in this work we have chosen a linear machine sequencing method.

2. Literature Review

Many researchers have discussed the linear sequencing of machines for solving flow layout problems. Houshyar and McGinnis [8] introduced a heuristic for assigning facilities to locations for the purpose of minimizing the travel distance traversed during work progress in a straight track. The established heuristic exhibited better performance than did the modified and classical lower bound methods.

The triangle assignment algorithm was used by Heragu and Kusiak [4] in solving the machine layout

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problems in an FMS. The computational time of the proposed algorithm was comparable to that of existing methods. Heragu and Kusiak [9] presented two efficient models: a linear continuous and linear mixed integer for facility layout problems. The models do not necessitate prior knowledge of site locations. The authors showed that the continuous models are more useful for solving facility layout problems than are other models presented in the literature.

Heragu and Alfa [3] experimentally analyzed simulated annealing-based algorithms; namely, a modified penalty algorithm, the simulated annealing algorithm, and a hybrid simulated annealing algorithm for single-row layout problems in facilities of unequal areas and for multi-row layout problems in facilities of equal areas. The authors concluded that the hybrid algorithm produces better quality solutions than do the first two algorithms, although the former involves slightly longer computational time.

Kouvelis and Chiang [10] implemented a simulated annealing procedure to determine a flow line (or single-row layout) under the assumptions that the number of machines is fixed and backtrack movements are allowed. The authors aimed to determine a machine sequence with minimum total backtrack distance.

Ho et al. [11] proposed two flow analysis methods for a multi-flow line layout design to realize shorter flow distances. The first method features a traditional line structure for analysis, whereas the second implements a network structure. The authors also developed a heuristic pattern-matching method for single-row layout problems in FMSs in which a linear machine sequence is initially constructed for the product that entails the largest number of operations.

Braglia [12] regarded the linear machine sequencing problem as a non-polynomial hard combinatorial problem. The number of possible sequences grows exponentially because the use of duplicate machines is allowed. Moreover, the set of all feasible sequences is not merely a set of simple permutations of a fixed number of machines given that the sequences must satisfy the different operation sequences of all products. Braglia determined a linear machine sequence with minimum expected movement of the machine handling device located between machines in a machine cell. The expected movement is determined by the frequency of part displacements between machines.

Wang et al. [13] formulated a model for minimizing the total material handling distance on a shop floor in both inter- and intra-cell facility layouts for cellular manufacturing systems. The authors used an improved simulated annealing algorithm to solve this problem.

Using a simulated annealing algorithm, Ho and Moodie [14] investigated a machine layout problem with a linear single-row flow line for an automated manufacturing system. The authors also investigated the effect of flow line characteristics on machine layouts. They provided vital information on selecting appropriate flow line analysis methods and determining appropriate evaluation criteria for different layout problems.

Chen et al. [15] addressed the problem of determining a common linear machine sequence for multi-products that have different operation sequences and facilities with a limited number of duplicate machine types. The authors intended to minimize the total flow distance traveled by products on this linear flow line by using a modified simulated annealing algorithm.

Diponegoro and Sarker [16] presented a two-stage solution methodology that simplifies computation and generates better solutions for reducing travel distances in production processes that involve sets of identical machines. This problem is often formulated as a tertiary assignment problem because of its combinatorial nature.

According to Hicks [17], layouts produced by a genetic algorithm-based optimization method significantly minimize material movement for a given work schedule in both greenfield and brownfield scenarios. A model for designing an FMS in one or multiple rows with genetic algorithms was discussed by Ficko et al. [18], who established the most favorable number of rows and the sequence of devices in an individual row by using genetic algorithms.

Chrysostomos and Vlachos [1] used the linear programming model for minimal backward flow to determine the optimal linear machine sequence in a manufacturing cell. They applied a modified ant colony algorithm (ACS) algorithm to the conditions and parameters of the linear machine layout problem. To determine the optimal linear placement of facilities with varying dimensions on a straight line, Anjosa et al. [19] introduced a semi-definite programming approach for the one-dimensional space-allocation problem, also known as the single-row facility layout problem.

Pillai et al. [20] identified a linear sequence that minimizes the total distance traveled by multiple items with different operation sequences. The authors regarded each type of machine available as limited and adopted a simulated annealing algorithm in determining the best solution. Solimanpur et al. [21] formulated the single-row machine layout problem as a non-linear 0-1 programming model in which the distance between the machines is sequence-dependent. They developed an ant colony algorithm to solve this problem.

To minimize the total cost of material handling and maximize the requirements of adjacent resources, Gengui et al. [2] developed a multiple-objective genetic algorithm approach with a local search method. On the basis of previously developed formulations, solution methodologies, and software packages, Singh et al. [22] discussed the current and future trends of research on facility layout problems. The authors observed a trend toward multi-objective approaches by developing facility layout software using meta-heuristics, such as simulated annealing, genetic algorithm, and concurrent engineering for facility layouts.

Andre and Amaral [23] proposed a mixed 0-1 linear program for the one-dimensional facility layout problem to minimize the weighted sum of distances, while Teo and Ponnambalam [24] proposed a hybrid ant colony optimization/particle swarm optimization (ACO/PSO) heuristic to solve single-row layout problems. For apparel manufacturing, Lin [25] proposed a hierarchical order-based genetic algorithm to minimize the moving distance between cutting pieces in a U-shaped single-row machine layout.

Ramazan et al. [26] and Jannat et al. [5] both considered the same two objectives in solving flow layout problems: minimizing material handling costs and maximizing closeness rating scores. Ramazan et al. proposed a simulated annealing algorithm to identify the non-dominated solution (Pareto optimal) set, while Jannat et al. developed a genetic algorithm for the multi-objective facility layout problem and determined the optimal facility location for a particular problem.

Satheesh Kumar et al. [27] employed an artificial immune system algorithm to minimize material handling costs both in single-row and loop layout problems in FMSs. Siva Kumar et al. [28] developed a simple heuristic to determine the optimal linear sequence that minimizes the flow distance traveled by products.

Dilip Datta et al. [29] developed a permutation-based genetic algorithm for arranging the facilities in a line with minimum cost. Giuseppe Aiello et al. [30] proposed a new multi-objective genetic algorithm (MOGA) based on slicing structure encoding for solving unequal area facility layout problems. Amir Sadrzadeh [31] proposed a genetic algorithm with the heuristic procedure to solve the multi-line layout problem.

Despite the considerable effort directed toward solving flow layout problems, most of these studies focused on the optimization of a single parameter only—flow distance. In practice, however, the total number of machines in a layout and the total investment cost of machines are equally important factors. In this work, we aim to determine a linear sequence of machine arrangement that minimizes total flow distance in units, total number of machines in the final linear sequence, and total investment cost of machines.

3. Problem Definition

The locations and number of machines in a linear machine sequence of a single-row layout design are keys to determining the flow distance of multi-products and total investment cost of machines. In facilities with duplicate machines and multiple products, the single-row layout design is considered a non-polynomial hard problem [12]. In this work, the linear sequence of machine arrangement is determined by three different methods: (i) Product sequence based on descending order of flow distances, (ii) Product sequence based on descending order of product due date, and (iii) Product sequence based on random selection.

This work is based on the following assumptions:

The number of products, demand for products, due date of products, machine type sequences, and individual costs of machines are known, along with the availability of duplicate machines.

The products always enter the first machine to which they are assigned in the final linear machine sequence.

The products' flow distances extend to the end of the respective machine types of the products without affecting the preceding flow.

The machines have sufficiently large capacities.

Backtracking is prohibited.

4. Mathematical Model

4.1 Total flow distance of products

The total flow distance of a product in units (td) is determined using Eq. 1. The constraints are presented in Eqs. 2–6:

$$td = \sum_{i=1}^{np} d_i (L_{il} - L_{if}) \qquad (1)$$

where

td – total flow distance;

d_i – i^{th} product flow distance;

L_{il} – i^{th} product's last machine location in the final machine sequence;

L_{if} – i^{th} product's first machine location in the final machine sequence;

np – number of products.

$$L_{ij+1} > L_{ij} \qquad (2)$$

$$L_{ij} > L_{i1} \qquad (3)$$

$$nm_k \leq ndm_k \quad (4)$$

where

L_{ij+1} – i^{th} product's $j+1^{th}$ machine location in the final machine sequence;

L_{ij} – i^{th} product's j^{th} machine location in the final machine sequence;

nm_k – number of k^{th} machines available in the final linear machine sequence;

ndm_k – number of duplicate k^{th} machine types available for use.

$$tm = \sum_{k=1}^{nmt} ndm_k \quad (5)$$

where

tm – total number of machines available for use;

nmt – number of machine types;

k – index that represents machine type k =1,2,3,…nmt.

$$nms \leq tm \quad (6)$$

where

nms – total number of machines available in the final linear sequence.

Equation 2 shows that the location of the $j+1^{th}$ machine should always be larger than the location of the j^{th} machine in the linear machine sequence. Equation 3 indicates that the location of the $j+1^{th}$ machine in the individual product machine sequence should always be larger than the location of the first machine in the linear machine sequence. According to Eq. 4, the number of k^{th} machines types available in the final linear machine sequence should be less than or equal to the number of duplicate k^{th} machine types available for use. The total number of machines is equal to the sum of the duplicates of individual machine types; this total is given in Eq. 5. Equation 6 shows that the total number of machines in the linear sequence must be less than or equal to the total number of machines available for use, including the duplicate machines.

4.2 Total number of machines in the final linear sequence

The minimum number of machines in the final linear sequence (nms) of the single-row layout design reduces both flow distance and initial investment. This reduction can be expressed using

$$nms = count(b[......]), \quad (7)$$

where b[……] represents the final linear machine sequence.

4.3 Investment cost of machines

Companies prefer to reduce not only their operation/manufacturing costs but also their initial investment. In the single-row layout design, the investment cost of machines is expressed by

$$tc = \sum_{k=1}^{nmt} c_k nm_k \quad (8)$$

where

tc – total investment cost of machines in the final linear sequence;

c_k – cost of the k^{th} machine type.

5. Proposed Heuristic for Evaluating Linear Sequence of Machines

In this work, the linear sequence of machine arrangement is determined by three different methods: (i) Product sequence based on descending order of flow distances, (ii) Product sequence based on descending order of product due date, and (iii) Product sequence based on random selection. The common heuristic has been developed and presented in this section. The product sequence selection given in Step 2 in the heuristic may vary depending on the above said three methods.

The detailed algorithm for determining the linear sequence of machine arrangement by the product sequence based on descending order of flow distances is given below.

Step 1: Read number of machine types (nm), number of duplicate machines in each type (mtn[]), number of products (np), number of machine type in each product (nmp[]), machine type sequence for each product (pseq[][]), flow distance of each product (pd[]), and product preference order based on due date (pdd[]).

Step 2: Arrange the product in descending order based on flow distance of the product and store in pno[].

Step 3: Assign the machine type for the first product's machine sequence and store in b[]. Update the availability of the machine type in mtn[].

Step 4: For each of the remaining products in pno[], conduct steps 5 through 12.

Step 5: For each machine type (mno) in the product sequence pseq[][], conduct Step 6.

Step 6: If the machine mno is unassigned, then add the machine in front of the existing machine sequence b[] and update its availability. Go to Step 5.

Step 7: If the machine type is assigned, check the machine type mno in the existing sequence b[]

Step 8: If available, check the availability of the remaining machine type of pseq[][] in b[].

Step 9: If all the machine types are available, then go to Step 4.

Step 10: If not, if the machine type mno is unassigned, then insert the mno in the appropriate location (the location that doesn't affect the existing product machine sequence in b[]) after the location of the previous machine type exist in the existing machine sequence b[] and update the availability. Go to Step 5.

Step 11: If the machine type mno is unassigned but the insertion in b[] affects the existing product sequence, then add the mno at the end of b[] and update the availability. Go to Step 5.

Step 12: If the machine type mno is assigned, then the existing sequence is not feasible and stop the program.

Step 13: Display the linear sequence of machine type b[]

6. Problems and Observations

We applied the proposed algorithm to solve the literature problems and additional problems; the ones discussed in this paper are the first five problems solved by Pillai et al. [20], Chen et al. [15], and Siva Kumar et al. [28], as well as problems that are randomly generated. Input data, such as the number of products and their machine type sequences, product demand, and product's processing order based on due date are listed in Table 1. The number of machine types and their duplicate numbers are listed in Table 2. The cost of individual machine types is listed in Table 3.

Table 1: Operation sequences and product demand of example problems

Problem no.	Products	Operation sequence	Product demand	Product's processing order based on due date
1 Pillai et al + Chen et al	1	2-3-4-6-8-9-7	20	II
	2	14-2-3-4-5-10-11-12	10	I
	3	2-4-6-8-9-13	15	III
	4	1-2-3-5-11-12	10	IV
2 Pillai et al	1	1-8-9-6-4	700	V
	2	5-3-2-7	600	I
	3	5-3-2-9	500	II
	4	3-7-6-4	400	III
	5	3-2-7-9-10	300	IV
3 Pillai et al	1	1-3-2-6-5	800	I
	2	4-6-1-7	400	III
	3	4-1-6-5	300	V
	4	4-3-2-5	200	II
	5	4-1-3-2	100	IV
4 Chen et al	1	14-13-7-15	34	I
	2	2-10-12-13	29	III
	3	11-15-5-3	94	IV
	4	15-5-1-4	89	II
5 Chen et al	1	4-5-3-9	69	V
	2	5-3-7-6	13	II
	3	13-7-12-9	113	IV
	4	8-5-3-14	72	III
	5	11-13-14-7	131	I
	6	2-5-1-10	36	VI
6	1	8-2-10-9-6	34	I
	2	4-8-6-5	2	III
	3	1-11-4-5	30	IV
	4	12-3-7-1	36	V
	5	10-9-5-7-2	48	II
7	1	4-6-8-1	8	VI
	2	7-1-8-2	15	V
	3	5-6-9-8-3	32	III
	4	3-5-1-8	50	I
	5	5-9-8-1-7	42	II
	6	4-6-2-9	29	IV
8	1	1-3-5-7	12	VII
	2	2-4-6-7	18	II
	3	3-5-7-1	15	IV
	4	4-2-3-7	16	III
	5	7-2-5-6	20	I
	6	1-3-2-6	13	VI
	7	5-4-7-6	14	V

Table 2: Machine Types and its Duplicates for the Example Problems

Problem no.	Machines types														
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
2	1	1	1	1	1	1	1	1	1	1					
3	2	1	1	1	1	2	1								
4	1	1	1	2	1	2	2	2	2	2	1	2	1	1	1
5	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
6	2	2	2	2	2	2	2	2	2	1	2	1	2		
7	2	1	2	2	1	1	2	2	2						
8	2	2	2	2	2	2	2								

Table 3: Machine Types and its Cost for the Example Literature Problems.

Machines types	Problem no.							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
1	8,788	84,565	10,000	8,788	21,011	20,831	24,121	12,315
2	6,589	74,325	15,000	6,589	28,752	12,380	4,546	14,445
3	3,512	59,874	16,000	3,512	26,354	22,658	25,742	19,854
4	6,541	39,998	12,000	6,541	17,655	24,658	27,159	16,547
5	3,254	47,775	11,000	3,254	21,357	17,230	26,738	15,487
6	9,874	22,225	13,000	9,874	16,554	16,660	18,822	13,221
7	6,547	14,411	14,000	6,547	11,357	12,557	21,612	11,315
8	8,541	15,455		8,541	30,699	6,088	979	
9	3,256	1,34,545		3,256	19,220	10,912	12,257	
10	1,111	6,57,884		1,111	12,632	27,943		
11	2,222			2,222	10,228	24,234		
12	3,333			3,333	24,998	8,132		
13	4,445			4,445	27,111	20,831		
14	5,554			5,554	28,478			
15				6,666				

Table 4: Computation Results

Problem no.	No. of machine types	No. of products	Method	Total flow distance in units	Total machine cost in Rs.	Total no. of machines in the sequence	Product's sequence	Optimal final linear sequence
			M1	475	73,567	14	1-3-2-4	1-14-2-3-4-6-8-9-7-13-5-10-11-12
1	14	4	M2	515	73,567	14	2-1-3-4	1-14-2-3-4-5-10-11-12-6-8-9-7-13
			M3	515	73,567	14	1-2-3-4	1-14-2-3-4-6-8-9-7-5-10-11-12-13
			M1	12800	11,51,057	10	1-2-3-4-5	5-3-2-7-1-8-9-6-4-10
2	10	5	M2	13200	11,51,057	10	2-3-4-5-1	1-8-5-3-2-7-9-6-4-10
			M3	15200	11,51,057	10	5-1-2-3-4	5-1-8-3-2-7-9-10-6-4
3	7	5	M1	9000	1,1,4000	9	1-2-3-4-5	4-6-1-7-1-3-2-6-5

			M2	8800	1,01,000	8	1-4-2-5-3	4-1-3-2-6-5-1-7
			M3	11000	1,01,000	8	5-2-4-3-1	4-1-3-2-6-1-7-5
			M1	890	58,562	12	3-4-1-2	2-10-12-14-13-7-11-15-5-3-1-4
4	15	4	M2	1519	58,562	12	1-4-2-3	11-2-10-12-14-13-7-15-5-1-4
			M3	1167	58,562	12	1-3-2-4	2-10-12-11-14-13-7-15-5-3-1-4
			M1	2388	2,96,406	14	5-3-4-1-6-2	2-4-8-5-3-11-13-14-7-12-9-1-10-6
5	14	6	M2	2554	2,96,406	14	5-2-4-3-1-6	2-4-8-5-3-11-13-14-7-6-12-9-1-10
			M3	3673	2,96,406	14	4-6-5-3-1-2	4-11-13-2-8-5-3-14-1-10-7-12-9-6
			M1	776	3,14,687	19	5-4-1-3-2	4-8-6-1-11-4-5-8-2-12-3-7-1-10-9-5-7-2-6
6	13	5	M2	640	2,69,198	17	1-5-2-3-4	12-3-7-1-11-4-8-6-5-8-2-10-9-6-5-7-2
			M3	1012	3,14,687	19	3-5-2-4-1	8-2-12-3-7-1-4-8-6-10-9-5-7-2-1-11-4-5-6
			M1	Infeasible solution				
7	9	6	M2	1174	2,34,430	13	4-5-3-6-2-1	3-5-7-1-8-4-6-2-9-8-1-7-3
			M3	1080	2,34,430	13	6-1-4-5-2-3	7-3-5-1-8-4-6-2-9-8-1-7-3
			M1	Infeasible solution				
8	7	7	M2	606	2,06,368	14	5-2-4-3-7-6-1	4-2-1-3-5-4-6-7-1-3-7-2-5-6
			M3	558	1,86,514	13	2-3-5-1-4-6-7	4-2-1-3-5-7-1-2-4-6-7-5-6

7. Computation Results and Discussion

The final linear machine sequence, product sequence, total flow distance, total machine cost, and total number of machines in the final linear sequence for the three methods are presented in Table 4.

M1 - Product sequence based on descending order of flow distances, M2 - Product sequence based on descending order of product due date, M3 – Product sequence based on random selection

The computational results of the three different methods are compared. In most of the cases, the products sequence based on descending order of flow distance provides better results compared with other two approaches because, in the other two approaches, the products sequences are selected based on random selection and due date.

All the proposed algorithms yield minimum flow distance, minimum number of machines, and minimum investment cost of machines because of the following reasons:

Machines are assigned not on the basis of the descending order of the flow distance of a product’s sequence.

The number of machines used in every machine type in the final linear machine sequence is reduced.

The unassigned machine types are incorporated at the front or back flow of the existing machine sequence, depending on availability.

If one of the machine types is assigned and it is available in the existing sequence, its availability in this sequence is verified even if the remaining machine types are unassigned. If any of the remaining machine types are unavailable in the existing sequence and are unassigned, then the machine type is incorporated at the back flow of the existing sequence without affecting the previous product machine type sequences.

8. Conclusion

The linear sequence of machines in a layout design determines the flow distance and investment cost of machines for multi-products of different operation sequences with a single or limited number of duplicate machines of each type. In this work, three different approaches are compared for constructing a linear sequence of machines with minimum total flow distance in units, total investment cost of machines, and total number of machine types arranged in the final linear sequence. It is concluded that the proposed approach is highly efficient both in individual objective functions and in combined objective functions, and it provides better practical support in making decisions while solving the problems inherent in multi-objective facility layout design.

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