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A Clustering-Based Approach to Machine Layout Problems with Application to Precision Fabrication Processes

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Abstract — Traditional precision fabrication companies have been facing higher material-handling costs in the production management problem. In this study, a clustering-based approach is developed and applied for grouping items and machine cells, respectively, for solving machine layout problems. Items are grouped using similarity measures based on the demand order information. Machine cells are grouped based on job routing analysis information. Then a quadratic assignment model based on throughput requirements and adjacency requirements is proposed for assigning machine cells to proper locations in a plant so as to minimize the total material-handling costs. The throughput and adjacency information is generated by using the job routing analysis. A novel heuristic, including ranking procedure, clustering procedure and interchanging procedure, is developed for solving the quadratic assignment model. A case study using real-world data collected from a local precision fabrication company is demonstrated. Also, a facility layout package FACTORY is utilized to evaluate the potential benefit of the proposed approach. Results suggest that the proposed approach significantly reduce the total material-handling costs.

Keywords — Machine layout, quadratic assignment problems, heuristic,

1. INTRODUCTION

Traditional precision fabrication companies have been facing several inherent characteristics of inflexibility and inefficiency in the production problem. The production management problem might be due to some possible causes, including: demand to produce many types of product each with small order quantities, need to operate similar manufacturing processes for many products with different specifications, desire to install many types of fabrication machine cell each with many quantities, etc. Due to these possible causes, many precision fabrication companies might face the problems of increasing material-handling costs and work-in-process inventory costs. In order to cope with these problems and maintain a competitive edge, most precision fabrication companies tend to introduce more advanced precision machines and manufacturing technologies so as to increase product quality and speed production rate. However, the machine layout problem can also play an important role and issue needed to be carefully investigated in hope to alleviate the problems associated with higher material-handling cost and work-in-process inventory cost.

For dealing with facility layout problems, three types of method, that is, fixed-position, process, and product, are commonly applied in the industry (Boothroyd *et al.*, 2002). Fixed-position layouts are common in project work where the end item is large and difficult to move. In a process layout, similar types of operations are clustered into functional work areas and each job is routed through the areas according to its routing sequence of operations. The product layout consists of all the necessary operations for producing a product arranged in a sequence on a line. Product layouts and process layouts represent two pure types of layouts at opposite ends of a continuum. Since many plants use different work processes with variety of constraints, the facility layout problem has been an important issue for investigation and study.

Irani and Huang (2000) developed a network of layout module for multiproduct facility problems and a systematic method for implementation of this design approach. Their layout modules allow for a single facility to have different types of layout configurations designed for different portions of its material-flow network. Al-Hakim (2000) adopted a slicing tree representation of a floor layout and developed a parallel genetic algorithm for solving their problem. Azadivar and Wang (2000) presented a facility layout optimization technique that took into consideration the dynamic characteristics and operational constraints of the system as a whole. Wang *et al.,* (2001) formulated a model to solve the facility layout problem in cellular manufacturing systems, assuming that the demand rate varies over the product life cycle and applied a simulated annealing algorithm for solving their model. Lee and Lee (2001) presented a shaped-based block layout approach for solving facility layout problem with unequal-areas and fixed-shaped and employed a hybrid genetic algorithm to find good solution. Sherali *et al.*, (2003) presents an improved mixed-integer programming model and effective solution strategies for the facility

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layout problem. They also developed several modeling and algorithmic enhancements that were demonstrated to produce more accurate solutions while also decreasing the solution effort required. Balakrishnan *et al.*, (2003) presented an effective and user friendly software, which uses two methods, simulated annealing and genetic algorithms to solve the facility layout problem. EL-Baz (2004) described a genetic algorithm to solve the facility layout problem in manufacturing systems design, considering the various material flow patterns of manufacturing environments of flow shop layout, flow-line layout with multi-products, multi-line layout, semi-circular and loop layout.

Dunker (2005) presented an algorithm combining dynamic programming and genetic search for solving a dynamic facility layout problem. Chen and Sha (2005) presented a heuristic approach for the generation of preferred objective weights to solve the multi-objective facility layout problem. They provided five phases in the proposed heuristic approach. Baykasoglu *et al.*, (2006) made use of the ant colony optimization algorithm to solve the dynamic layout problem by considering the budget constraints. Ertay *et al.* (2006) proposed a decision-making methodology based on data envelopment analysis for evaluating facility layout design. McKendall and Shang (2006) developed hybrid ant systems to solve the dynamic facility layout problem, considering the problem of arranging and rearranging, when there are changes in product mix and demand, manufacturing facilities such that the sum of material handling and rearrangement costs is minimized. McKendall *et al.*, (2006) developed two simulated annealing heuristics developed for the dynamic facility layout problem. Amaral (2006) proposed a new mixed-integer linear programming model and developed an exact solution algorithm for solving this problem. Konak *et al.*, (2006) presented a mixed-integer programming formulation to find optimal solutions for the block layout problem with unequal departmental areas arranged in flexible bays. Aiello *et al.*, (2006) developed an approach to the multi-objective facility layout problem in two steps: determining the Pareto-optimal solutions by employing a multi-objective constrained genetic algorithm and carrying out the optimal solution by means of the multi-criteria decision-making procedure Electre. Kulturel-Konak (2007) presented the most recent advancements in designing robust and flexible facilities under uncertainty, namely dynamic and stochastic facility layout problems and briefly reviewed recent approaches in the related categories. Anjos and Vannelli (2006) presented a new framework for efficiently finding competitive solutions for the facility-layout problem, based on the combination of two new mathematical-programming models. The first model is a relaxation of the layout problem and is intended to find good starting points for the iterative algorithm used to solve the second model. The second model is an exact formulation of the facility-layout problem as a nonconvex mathematical program with equilibrium constraints. Meller *et al.*, (2007) presented a new formulation for the facility layout problem based on the sequence-pair representation.

Singh and Sharma (2006) presented a state-of-the-art review of papers on facility layout problems with an aim to deal with the current and future trends of research on facility layout problems based on previous research including formulations, solution methodologies and development of various software packages. Drira *et al.* (2007) suggested a general framework to analyze the literature of facility layout design and pointed out several research directions. At some point, proliferation and diversity in products can make the choice of facility layouts more complicated. One solution to the problem of managing proliferation and diversity is to use group technology to identify similarities among different products and group them accordingly, and then produce each group in a single place with same equipment (Burbidge 1997). The applications of group technology involves at least two things: (1) forming a cluster of products or parts that are similar in terms of processing requirements and (2) forming a cluster of operations, machines, workers and tools. One of approaches used for configuring groups is cluster analysis. For a review of cluster analysis with application to facility layout design, one can see the research efforts from McAuley (1972), Waghodekar and Sahu (1984), Ballakur and Steudel (1987), and Cheng *et al.,* (1995), among others. Such an approach can be able to determine the product-machine groups to form machine cells and specific layouts for the machine cells.

Regarding the application of cluster analysis, there are several approaches for solving the machine layout problem. In the early years, Koopmans and Beckman (1957) formulated the machine layout problem as a quadratic assignment problem. They pointed out that the quadratic assignment model might be a useful tool for solving the machine layout problem. Seppanen and Moore (1970) pointed out that the machine layout problem could be divided into two sub-problems, namely, the adjacency problem and the block layout problem, and each sub-problem could be solved using suitable techniques. Love and Wong (1976) solved this problem as a linear mixed-integer programming problem. Drezuer (1980) proposed a nonconvex mathematical programming technique for the machine layout problem. Heragu and Kusiak (1987) devised a solution that minimizes the total material handling costs between all pairs of machine cells. Foulds (1983) tackled this problem using an adjacency requirements formulation and sought a solution that maximizes the sum of closeness ratings. Heragu and Kusiak (1991) applied a linear continuous problem and efficient models for the machine layout problem. Meketon (1987) utilized simulation techniques to study the performance of a number of approaches explored for machine layout problems. Wascher and Merker (1997) presented a graph theoretic formulation and two heuristics for solving the machine layout problem. Later, they proposed a test procedure for evaluating several heuristics for the adjacency problem in machine layout planning problems.

In this study, a mix-integer quadratic assignment model based on throughput requirements and adjacency requirements is presented. The information for both throughput requirements and adjacency requirements is generated by using a job routing analysis from customer demand orders. Then a novel heuristic is developed for assigning machine cells to possible locations so as to minimize the total material-handling cost. Finally, a case study is performed to illustrate the potential benefits of this proposed approach.

2. PROBLEM FORMULATION

In the machine layout problem a given number of machine cells have to be laid out on a plant. There are at least two factors that might determine the volume-distance measure through which items must be moved: the layout of the machine cells and the routing sequence of operations to produce the items. Assume that all the machine cells are positioned along the transportation route with longest side parallel to the direction of material flow from an input/output (I/O) location. There are at least two types of flow needed to be considered. One is the adjacency flow between each pair of machine cell and the other the from between each machine and the I/O location. Suppose there are *K* machine cells to be assigned to *K* locations. Define a flow matrix and a distance matrix whose elements are, respectively,

f_{ik} = the adjacency flow volume from machine cell i to machine cell k;

d_{jl} = the distance between location j and location l;

t_i = the distance between location i and I/O location;

r_j = the flow requirement between location j and I/O location;

x_{ij} = 1, if machine cell i is assigned to location j; 0, otherwise;

x_{kl} = 1, if machine cell k is assigned to location l; 0, otherwise.

A quadratic assignment problem for the machine layout problem may be formulated as follows.

Minimize $$z = \frac{1}{2}\sum_{i=1}^{K}\sum_{j=1}^{K}\sum_{k=1}^{K}\sum_{l=1}^{K} f_{ik} d_{jl} x_{ij} x_{kl} + \sum_{i=1}^{K}\sum_{j=1}^{K} t_i r_j x_{ij} \tag{1}$$

subject to $$\sum_{i=1}^{K} x_{ij} = 1, \qquad j = 1, \ldots, K, \tag{2}$$

$$\sum_{j=1}^{K} x_{ij} = 1, \qquad i = 1, \ldots, K, \tag{3}$$

$$x_{ij} \in \{0, 1\}, \qquad \forall i,\ j. \tag{4}$$

The first term in the objective function (1) describes the total flow between all pairs of machine cells, which represents the adjacency requirements. The second term denotes the total throughput flow from the I/O location to each of the machine cells, which represents the throughput requirements. Hence, the objective function spells out the total material-handling volume-distance flow. Note that the distance matrix is symmetry and the flow is unidirectional, the coefficient of one half is added to the first term in the objective function. In this model, the objective function intends to minimize the total material-handling cost, which is represented by the combined throughput volume-distance requirements from each machine cell to the I/O location and the adjacency volume-distance flow between each pair of machine cell. Constraint (2) ensures that only one machine cell is assigned to one location and constraint (3) ensures that only one location is allowed for one machine cell. Constraint (4) restricts the variable values to be either zero or one.

The information of both throughput flow from the I/O location to each machine cell and adjacency flow between each pair of machine cells is generated using a job routing analysis based on customer demand orders. In the job routing analysis, the manufacturing process for each product type is analyzed and described by an operational flow chart. All the operations and the associated machine cells are sequenced along the manufacturing process for each product type. Then the customer demand orders are collected for generating the flow information. From the flow information, we obtain the material flow matrix among machine cells and the throughput requirements for each machine cell. Also, the distance matrix of all tentative locations is obtained by measuring the travel distance according to the job routing process.

3. SOLUTION METHODS

The developed optimization model for machine layout problems is one type of 0-1 quadratic assignment problems with a nonlinear objective function and linear constraints. This type of problems is *NP*-hard and can be solved by implicit enumeration algorithms (Bazarraa and Sherali 1982). They also suggested that linearization techniques can be used to streamline the solution methods. However, the core requirements became too large for the mixed integer programming code they used as the problem size increases.

Due to a special structure and property exhibited in the developed model, it is possible to solve this 0-1 quadratic assignment problem without the need of utilizing the linearization approach and the standard quadratic problem algorithms. The idea comes from the fact that the developed mix-integer quadratic assignment problem can be decomposed into two sub problems by looking at each term in the objective function separately. If there exists no adjacency flow among all machine cells, we can set $f_{ik} = 0, \quad \forall\, i,k$. Then the mix-integer quadratic assignment problem accordingly reduces to the following linear assignment problem.

$$\text{Minimize} \quad z = \sum_{i=1}^{K}\sum_{j=1}^{K} t_i r_j x_{ij} \tag{5}$$

subject to (2), (3) and (4).

This linear assignment problem can be efficiently solved by the use of a greedy method without appealing to one of the standard algorithms. The procedure from the greedy method, named ranking procedure in this study, is to put the machine cell with the largest throughput requirements in the location with the smallest travel distance, put the machine cell with the next largest throughput requirements in the location with the next smallest travel distance, and so on. Below, we present an effective ranking procedure that is capable of finding an optimal assignment for the reduced equation (5).

Ranking Procedure

Step 1: Sequence the machine cells according to the throughput requirements from large to small, that is, $r_1 \ge r_2 \ge \dots \ge r_K$
Step 2: Sequence the locations according to the travel distances from short to long, that is, $tt_1 \leqq tt_2 \leqq \cdots \leqq tt_K$.
Step 3: Perform assignment of machine cells to locations by first assigning the largest machine cell r_1 to the shortest location t_1; assigning the next largest machine cell r_2 to the next shortest location t_2; and so on.
Step 4: Compute the total volume-distance flow as the upper bound for the problem.

Next, we observe that if all the throughput requirements from each machine cell to the I/O location in the objective function are ignored for all machine cells, then the objective function (1) is reduced as follows.

$$\text{Minimize} \quad z = \frac{1}{2}\sum_{i=1}^{K}\sum_{j=1}^{K}\sum_{k=1}^{K}\sum_{l=1}^{K} f_{ik} d_{jl} x_{ij} x_{kl} \tag{6}$$

subject to (2), (3) and (4).

The solution to the reduced mix-integer quadratic assignment problem requires that those machine cells that share with higher adjacency flow should be allocated in the adjacent location. Hence, we present a clustering procedure to obtain the grouping structure of machine cells by the associated adjacency flow information. The idea for the clustering procedure is to maximize the within-cluster adjacency flow and in the same time to minimize the between-cluster adjacency flow. Suppose we want to obtain a grouping structure form all the existing *M* machine cells. The developed clustering procedure follows.

Clustering Procedure

Step 1: Start with M groups, each containing a single machine cell and a $M \times M$ symmetric matrix of adjacency flow, $F = \{f_{ik}\}$.
Step 2: Search the largest adjacency flow in the flow matrix for the nearest pair of machine cell groups. Let the flow measure between most groups U and V be $f_{UV}(U, V)$.
Step 3: Merge groups U and V. Label the newly formed cluster. Update the elements in the adjacency flow matrix by (i) deleting the rows and columns corresponding to groups U and V, and (ii) adding a row and column that contain the adjacency flow between group (U, V) and the remaining groups.
Step 4: Repeat Steps 2 and 3 a total of M-1 times. Record and identify the merged groups and the levels where merges take place.

The obtained grouping structure is then applied to modify the machine cell location assignment obtained from the ranking procedure. The idea comes from the fact that the machine cells within the same cluster in the grouping structure should appear in the nearest locations if possible. Otherwise, the relocation of those machine cells to the adjacency area can be considered so as to reduce the total volume-distance flow. The proposed interchange procedure begins with the first level in the grouping structure, in which machine cells in this group should be considered to reshuffle. If those machine cells in the same level are already allocated in the adjacent location, then we proceed to the next level of the grouping structure. Otherwise, those machine cells that are allocated in the distanced locations are moved forward to the target machine cell, which is already allocated to be nearest to the I/O location. The proposed interchange procedure is stated as follows.

Interchange Procedure

Step 1: Begin with the first level of the grouping structure. If all machine cells in the same group are already allocated in the adjacent locations, then go to Step 5. Otherwise, proceed to Step 2.
Step 2: Denote the machine cell with largest throughput requirements as the target item and the remaining non-adjacent machine cells as the non-target items. Among the non-target items, select the one with the largest throughput requirement as the candidate item. Proceed to Step 3.
Step 3: Move the candidate item forward to the location next to the target item. Those items that are not in the current level and being currently allocated next to the target item are shifted next to the candidate item. Compute the total volume-distance flow. If the computed total volume-distance flow is improved, then proceed to Step 4. Otherwise, restore the candidate item to the original location. Go to Step 5.
Step 4: If there exist some other non-target items in the same group that can be served as a candidate for rearrangement, select one as the candidate item and return to Step 3. Otherwise, proceed to Step 5.
Step 5: If all of the levels in the grouping structure are examined, stop. Otherwise, enter the next level of the grouping structure and return to Step 2.

The developed heuristic procedures, including the ranking procedure, the clustering procedure, and the interchange procedure, were coded in Borland C++ programming language. The compiled program ran on a Pentium II 266 PC with 64 MB RAM.

4. IMPLEMENTATION

Real-world data collected from a local precision fabrication company that has produced many types of products using a variety of machine cells is used for the illustrative case study. The customer demand orders shown in Table 1 contain data of the major product types and the order quantity information in this study. With the problem in hand, the machine layout planning is very important in the process of designing a manufacturing unit. We believe that a carefully designed layout can reduce material-handling cost and bring about strategic competitive advantage.

Table 1. Item types and monthly demands for major products

Product Type	Monthly Demand
1. Combustion Chamber	4,500
2. Bearing	1,500
3. Bar	2,000
4. Starting Handle	2,500
5. Governor Lever Assembly	2,000
6. Mount F. I. Pump	1,000
7. Bonnet Assembly	2,000
8. Support for Valve Lever and Finished Product	2,800

Initially, job routing analysis was performed and the operational flow diagram for each major product type was obtained. Table 2 displays the operational flow charts for eight major product types and the operational flow charts were analyzed using the manufacturing process information. By the operational flow charts, we sort the entire variety of machines into twelve types of machine cells. Table 3 provides this information for each machine cell type.

Table 2. Operational flow diagram for major products

Product Type	Operation Flow Charts
1. Combustion Chamber	CNC (CNC01, CNC02, CNC03) / Operation on CNC → Drill2 (D6) / Drilling noncenter hole → Drill3 (D10, D11) / Pierce the hole → Tlathe (L4, L5, L6, L7) / Remove the flash
2. Bearing	CNC (CNC01 ,CNC02, CNC03) / Operation on CNC → Mill (M1, M2) / Operation on Mill → Sander (S3, S4) / Remove rough edges → Drill2 (D9) / Pierce the hole → Thread (G1, G2, G3, G4) / Generating the screw thread → Subct / Subcontract (HeatTreatment,Grinding) → Assemble / Insert center pin
3. Bar	Tlathe (L4, L5, L6, L7) / Piercing on Table lathe → Subct / Subcontract (HeatTreatment)
4. Starting Handle	CNC (CNC01, CNC02, CNC03) / Operation on CNC → Mill (M1, M2) / Operation on Mill → Drill2 (D1, D2, D3, D4, D5) / Pierce the hole → Subct / Subcontract (HeatTreatment,Grinding) → Assemble / Insert center pin
5. Governor Lever Assy	Sander (S3, S4) / Remove rough edges → Drill2 (D6, D7, D8, D9) / Pierce the hole ← Thread (G1, G2, G3, G4) / Generating the screw thread
6. Mount F.l. Pump	Sander (S3, S4) / Remove rough edges → Drill2 (D6, D7, D8, D9) / Pierce the hole
7. Bonnet Assy. Finished Product	Hlathe (L1, L2, L3) / Lathing Bottom → Drill4 (D12, D16) / Pierce the hole → Paint / Painting c001 → Assemble / Assemble Bonnet Assy & Shaft Hlathe (L4, L5, L6, L7) / Lathing Shaft → Smill (M3, M4) / Milling Shaft → Assemble / Assemble Bonnet Assy & Shaft
8. Support for Lever & Finished Product	Hlathe (L1, L2, L3) / Embellish raw material → CNC (CNC01, CNC02, CNC03) / Operation on CNC → Mill (M1, M2) / Milling process → Thread (G1, G2, G3, G4) / Generating the screw thread → Assemble / Assemble Support for valve with two Rocker Arm Assy Hlathe (L1, L2, L3) / Embellish raw material → Mill (M1, M2) / Milling process → Drill1 (D1, D2, D3, D4, D5) / Pierce the hole → Drill1 (D1, D2, D3, D4, D5) / Pierce the hole → Assemble / Assemble Support for valve with two Rocker Arm Assy

Table 3. Types and codes of machine cells

Machine Cell	Code	Unit	Description
1. CNC	M1	CNC01, CNC02, CNC03	Perform precision fabrication
2. Hlathe	M2	L1, L2, L3	Embellish raw material
3. Tlathe	M3	L4, L5, L6, L7	Pierce on table lathe
4. Mill	M4	M1, M2	Milling process
5. Smill	M5	M3, M4	Milling shaft
6. Drill1	M6	D1, D2, D3, D4, D5	Pierce the holes for support and rocker arm assembly
7. Drill2	M7	D6, D7, D8, D9	Pierce the holes for governor lever assembly
8. Drill3	M8	D10, D11	Pierce the holes for combustion chamber
9. Drill4	M9	D12, D13, D14, D15, D16	Pierce the holes for bonnet assembly
10. Thread	M10	G1, G2, G3, G4	Generate the screw threads for bearing and support
11. Sander	M11	S1, S2, S3, S4	Remove rough edge for bearing and mount pump
12. A/O	M12	None	Final assembly

The existing machine layout before the implementation of the approach is shown in Figure 1 by using the facility layout package, FACTORY software (1997). The entire floor space in the plant is partitioned into twelve block locations and one I/O point. Table 4 shows the distance matrix for twelve block locations. The distance matrix provides the distances between the I/O point and each of the twelve block locations. Table 5 shows the adjacency flow between all pairs of machine cells and the throughput flow from the input/output point to each of twelve machine cells. The adjacency flow information and the throughput flow information were generated from the monthly demand order data and the operational flow diagram.

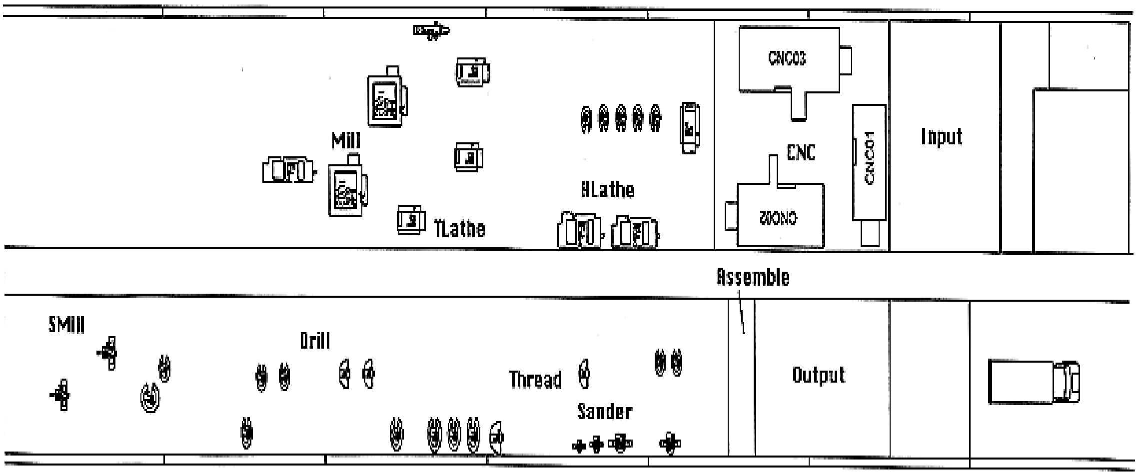

Figure 1. The existing machine layout before improvement

Table 4. Distance matrix of paired blocks (measured in meters)

	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12	I/O
B1	0	8.6	9.2	11.6	13.2	14.6	17.2	17.6	20.6	21.2	23.6	25.2	13.6
B2	8.6	0	7.6	10	11.6	13	15.6	16	19	19.6	22	23.6	17
B3	9.2	7.6	0	7.6	9.2	10.6	13.2	13.6	16.6	17.2	19.6	21.2	17.6
B4	11.6	10	7.6	0	8.6	10	12.6	13	16	16.6	19	20.6	20
B5	13.2	11.6	9.2	8.6	0	6.6	9.2	9.6	12.6	13.2	15.6	17.2	21.6
B6	14.6	13	10.6	10	6.6	0	9.6	10	13	13.6	16	17.6	23
B7	17.2	15.6	13.2	12.6	9.2	9.6	0	6.6	8.6	9.2	11.6	13.2	25.6
B8	17.6	16	13.6	13	9.6	10	6.6	0	10	10.6	13	14.6	26
B9	20.6	19	16.6	16	12.6	13	8.6	10	0	7.6	10	11.6	29
B10	21.2	19.6	17.2	16.6	13.2	13.6	9.2	10.6	7.6	0	7.6	9.2	29.6
B11	23.6	22	19.6	19	15.6	16	11.6	13	10	7.6	0	8.6	32
B12	25.2	23.6	21.2	20.6	17.2	17.6	13.2	14.6	11.6	9.2	8.6	0	33.6

Note: B1 represents Block1; B2 represents Block2; and so on.
I/O represents the input/output point.

Table 5. Material flow matrix for each pair of machine cells and throughput requirement for each machine cell

	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	r_i
M1	0	2800	0	6800	0	0	4500	0	0	0	0	0	8500
M2	2800	0	0	5600	0	0	0	0	2000	0	0	0	10400
M3	0	0	0	0	2000	0	0	4500	0	0	0	6500	4000
M4	6800	5600	0	0	0	10900	0	0	0	0	1500	0	0
M5	0	0	2000	0	0	0	0	0	0	0	0	2000	0
M6	0	0	0	10900	0	0	0	0	0	5600	0	5300	0
M7	4500	0	0	0	0	0	0	4500	0	3500	4500	1000	0
M8	0	0	4500	0	0	0	4500	0	0	0	0	0	0
M9	0	2000	0	0	0	0	0	0	0	0	0	2000	0
M10	0	0	0	0	0	5600	3500	0	0	0	0	9100	0
M11	0	0	0	1500	0	0	4500	0	0	0	0	0	3000
M12	0	0	6500	0	2000	5300	1000	0	2000	9100	0	0	0

Note: M1 represents machine cell 1; M2 represents machine cell 2; and so on.
r_i represents the throughput requirements for machine cell i.

The proposed heuristic was then applied to improve the machine layout plan. The detailed computational procedures, including ranking, clustering, and interchanging, are shown in Table 6. The total number of loops required to obtain the final solution is eleven and the total volume-distance flow is 1,281,680. Table 7 presents the final solution to display how the better machine-location assignment is for the case problem by the proposed approach. By employing a personal computer, it took 0.047 CPU seconds for the developed heuristic to get this solution, whereas the AMPL-CPLEX package (1997) took 2,786 CPU seconds. The obtained solution was displayed in Figure 2 using a facility layout package, the FACTORY software (1997).

The FACTORY software provides one useful module, the FLOW module, for evaluating alternative layout designs. So the FLOW module was further utilized to compare the obtained machine layout with the existing one in terms of the potential benefit. Using the FLOW module in the FACTORY package and the monthly demand order information, the total material handling distances are 2,824,360 feet for the existing machine layout and 905,603 feet for the obtained one, respectively. This result indicates significant reduction in the total material-handling cost by the proposed approach.

Table 6. Detailed computational procedures using the heuristic

Loop No.	Description	With Improvement	Objective Value
1	Shift {M6} to {M4}	No	1484880
2	Interchange {M10} with {M12}	Yes	1472560
3	Shift {M12, M10) to {M4, M6}	Yes	1389600
4	Shift {M4, M6, M12, M10} to {M1}	Yes	1328600
5	Shift {M3} to {M4, M6, M10, M12, M1}	No	1328600
6	Shift {M3, M4, M6, M10, M12, M1} to {M2}	No	1328600
7	Shift {M7} to {M2, M3, M4, M6, M10, M12, M1}	No	1328600
8	Shift {M8} to {M7, M2, M3, M4, M6, M10, M12, M1}	No	1328600
9	Shift {M11} to {M8, M7, M2, M3, M4, M6, M10, M12, M1}	Yes	1281680
10	Shift {M5} to {M11, M8, M7, M2, M3, M4, M6, M10, M12, M1}	No	1281680
11	Shift {M9} to {M5, M11, M8, M7, M2, M3, M4, M6, M10, M12, M1}	No	1281680

Table 7. Final solution for the case problem by the heuristics

Block	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12
Machine Cell	Hlathe (M2)	CNC (M1)	Mill (M4)	Sander (M11)	Drill1(M6)	Drill2(M7)	A/O (M12)	Thread (M10)	Drill3 (M8)	TLathe (M3)	SMill (M5)	Drill4 (M9)
Objective Value							1281680					
CPU Time in sec.							0.047					

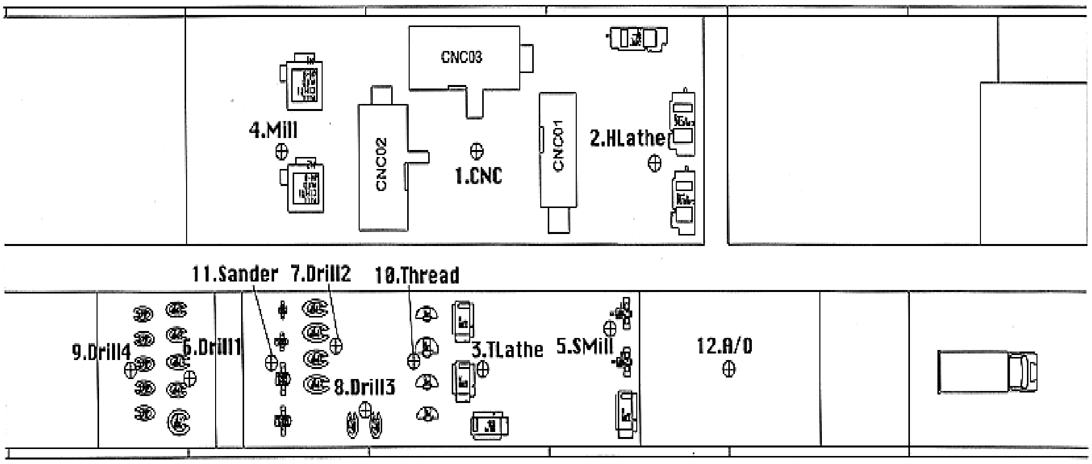

Figure 2. The achieved machine layout by the proposed approach

Furthermore, we compared the computational performance of the proposed heuristic with one of the well-known optimization packages, the AMPL-CPLEX software, using 9 test problems. The computational results shown in Table 8 suggest the proposed heuristic outperforms the AMPL-CPLEX package. In addition, this version of AMPL-CPLEX package can be only used to solve the mix-integer quadratic assignment problem with no more than thirteen item types, while the proposed heuristic can be used to solve larger scale of problems. One issue that the AMPL-CPLEX package cannot be applied to solve large scale problems might be due to the limitation of storages provided by this software. One can guess that this issue can be solved and improved a lot in the new version.

Table 8. Comparison of CPU times for AMPL-CLPEX package and the proposed heuristics

Prob. No.	No. of Var.	No. of Const.	AMPL-CPLEX			The Heuristics			Gap between two Objective Values in %
			Total No. of Branch	CPU sec.	Objective Value	Total No. of Loops	CPU sec.	Objective Value	
1	144	24	364	2795.32	1281680	11	0.035	1281680	0
2	169	26	462	7287.85	1313680	12	0.038	1326600	0.9
3	196	28	*	*	*	13	0.03	1568760	N/A
4	225	30	*	*	*	14	0.028	1607780	N/A
5	256	32	*	*	*	15	0.034	1688120	N/A
6	289	34	*	*	*	16	0.036	1768200	N/A
7	324	36	*	*	*	17	0.044	1830400	N/A
8	361	38	*	*	*	18	0.045	1895200	N/A
9	400	40	*	*	*	19	0.064	1935360	N/A

Note: 「*」 indicates the AMPL-CPLEX package can't solve this problem.

5. CONCLUDING REMARKS

The machine layout planning is a crucial step in the designing manufacturing systems for a plant. The machine layout techniques play an important role in reducing the total material-handling costs. A mix-integer quadratic assignment model based on throughput requirements and adjacency requirements has been presented for solving the machine layout problem arising in precision fabrication plants. A novel heuristic is exploited for assigning machine cells to candidate locations in the hope of minimizing the total material-handling cost. Results of a case study indicate that the proposed approach can significantly reduce the material-handling cost. The proposed heuristic can be used to tackle the machine layout problem in precision fabrication plants when both the adjacency requirements and the throughput requirements are imposed.

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