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Facility Layout

Xiaohong Suo
China Institute of Industrial Relations, Beijing,
P.R.China

1. Introduction

The facility layout problem is concerned with finding the most efficient non-overlapping arrangement of n indivisible departments with unequal area requirements within a facility. Generally, about 20%-50% of the total operating expenses in manufacturing are attributed to material handling costs. Effective facility layout could reduce these costs by 10%-30% annually. Moreover, good facility planning could also improve the material handling efficiency, reduce the throughput time, decrease the space utilization area of manufacturing system, etc. So, the facility layout affects the total performance of manufacturing system, such as, material flow, information flow, productivity, etc.

Facility layout, being a significant contributor to manufacturing performance, has been studied many times over the past decades. Raman et al. showed that facility layout has a direct impact on operational performance, as measured by manufacturing lead time, throughput rate, and work-in-process (WIP).

2. Classification of facility layout problem

It is well known, facility layout problem is concerned with the allocation of activities to space such that a set of criteria are met and/or some objectives are optimized. There are numerous derivations for the facility layout problems in manufacturing systems, which have been investigated in Table 1. These derivations can be classified into six categories (product, process, equipment, production, manufacturing system and company). Any changes in items of these six categories can lead to facility layout problem. Once one item changes, other items will change correspondingly, e.g., the introduction of new products results in changes in process and equipment. Generally, combinations of items of these six categories are the derivations for the facility layout problem.

When the flows of materials between the departments are fixed during the planning horizon, facility layout problem is known as the static (single period) facility layout problem (SFLP). Researchers had paid more attentions to SFLP, and now SFLP has two new trends. With more fierce competitive in the global market, facility layout must react on the changes in designs, processes, quantities, scheduling, organizations, and management idea rapidly. Once these items change frequently, manufacturing systems must be reconfigurable and their structure must be modified as well. However, SFLP can hardly meet this demand. Company need to design a flexible layout which is able to modify and expand easily the original layout. Flexibility can be reached by modular devices, general-purpose devices and material handling devices. The trends of SFLP are shown in Fig.1. Under a volatile environment, SFLP need to add flexibility to meet the production requirement. Approaches to get flexibility for SFLP include to modify the SFLP and to increase the robustness of the SFLP. Gradually, SFLP develops these two approaches to the dynamic facility layout problem (DFLP) and robust layout, respectively.

Up to now, there are existing three basic types of layout problem, including SFLP, DFLP and robust layout problem. Research on the relationships among SFLP, DFLP and robust layout is important due to the impact of the types of layout problem on productivity, quality, flexibility, cost, etc. How to select the suitable type of layout problem is an urgent task. The classification procedure of facility layout problem is shown in Fig.2, where researchers choose the appropriate type of layout problem based on the judgment conditions. The judgment conditions include whether the material handling flows change over a long time or not, and whether it is easy for rearrangement or not when the production requirement changes drastically. If the material handling flows change over a long time, choose DFLP or robust layout; if not, choose SFLP. If rearrangement is easy when the production requirement change drastically, choose DFLP; if not, choose robust layout.

No. Classify	1	2	3	4	5
Product	Increase or decrease in the demand for a product	Addition or deletion of a product	Changes in the design of a product	Introduction of new products	
Process	Changes in the design of process	Replacement of characteristics of process	Installation of new processes		
Equipment	Installation of new equipment	Replacement of one or more pieces of equipment			
Production	Failure to meet schedules	High ratio of material handling time to production time	Excessive temporary storage space	Bottlenecks in production	Crowded conditions
Manufacturing systems	Conflict between productivity and flexibility in general manufacturing systems	Flexibility does not meet the demands of changes in product mixes of FMS.			
Company	Adoption of a new safety standard	Organizational changes within the company	A decision to build a new plant		

Table 1. Derivations for facility layout in manufacturing systems

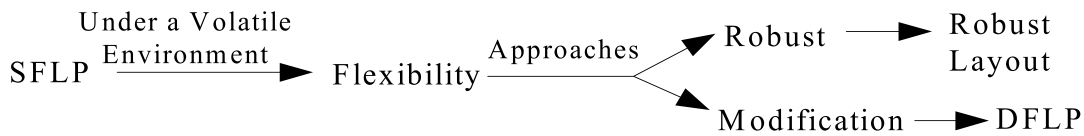

Fig. 1. Trends of SFLP

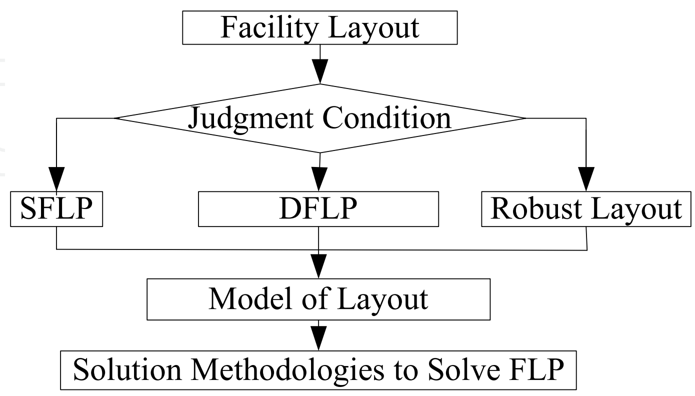

Fig. 2. Classification procedure of facility layout problems

2.1 Relationships among SFLP, DFLP and robust layout

Due to the impact of the locations of facility on material handling costs, throughput, and productivity of the facility, facility layout is an important module of manufacturing systems design. The FLP is the arrangement of departments within a facility with respect to some objective. The most common objective considered is the minimization of material handling cost. Material handling costs are determined based on the amounts of materials that flow between the departments and the distances between the locations of the departments. SFLP is appears when the flows of materials between departments are fixed during the planning horizon, which can be formulated as a quadratic assignment problem (QAP). So, SFLP is used under the static environment. When the flows of material between departments change during the planning horizon, this problem is known as the dynamic (multiple-period) facility layout problem (DFLP) [1]. Therefore, DFLP is widely used when the condition is changeable and the future demand of product can be forecasted. A robust layout is one that is good for a wide variety of demand scenarios even though it may not be optimal under any specific ones [2]. A robust layout procedure considers minimizing the total expected material handling costs over a specific planning horizon. Robust layout is selected when the demand is stochastic and the re-layout is prohibited.

2.1.1 SFLP vs. DFLP

SFLP Converting to DFLP.

Fiercer competition of the world makes SFLP covert to DFLP. Under today's changeable market situation, demand is changed irregularly from one production period to another. Generally, 40% of a company's sales come from new products, *i.e.* products that have only recently been introduced [3]. When these changes frequently occur and the location of an existing facility is a decision variable, SFLP convert to DFLP. The procedure of SFLP converting to DFLP is given in Fig. 3. The changes in product, process, equipment, etc. can bring on the facility layout problem. If the material flows are consumed to be constant, SFLP is sufficient. However, this assume are contradiction with the practice production. In order to correct the deficiency, SFLP will be converted to DFLP.

During the process of SFLP converting to DFLP, rearrangement costs arise. The changes in locations of facility can reduce the material flows between department pairs during a planning horizon. Meanwhile, rearranging the locations of facility will result in some shifting (rearrangement) costs depending on the departments involved in this shift. The procedure for rearrangement costs is illustrated in Fig. 4. Generally, when the products change often and the facility location is static, the material flows are increased drastically. In order to reduce the material flows, the facilities are shifted to different location which will result in the rearrangement (shifting) costs. The DFLP is based on the anticipated changes in flow that will occur in the future. Moreover, the future can be divided into any number of time periods, and a period may be defined in months, quarters, or years. In addition, different periods can be of different lengths [4].

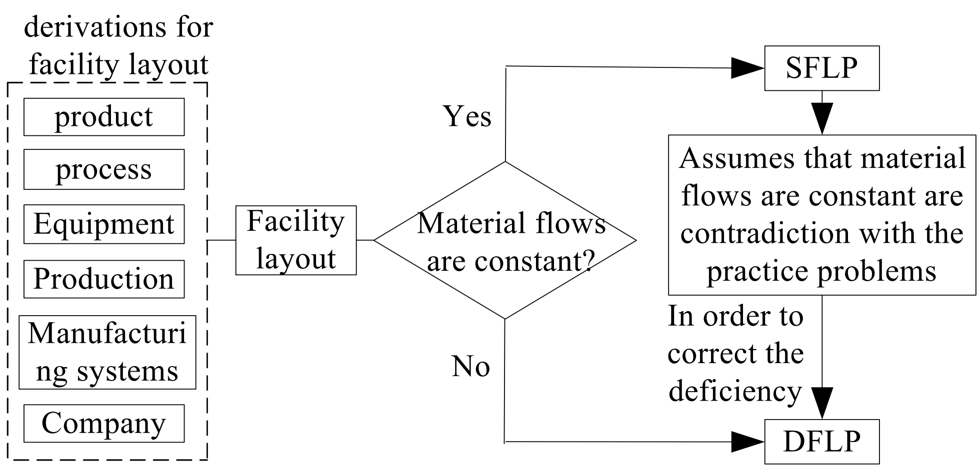

Fig. 3. Procedure of SFLP converting to DFLP

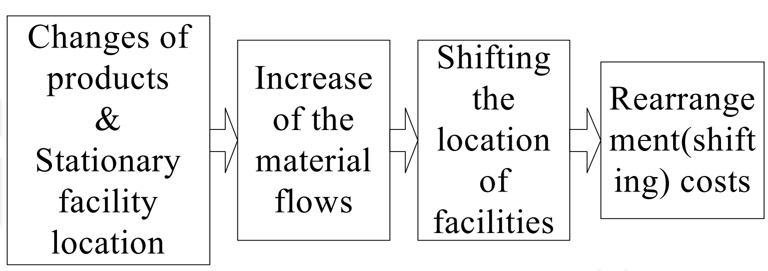

Fig. 4. Procedure for rearrangement costs in DFLP

SFLP for each period and rearrangement are the two parts of DFLP. For DFLP, it is assumed that the flow data during each period remains constant, respectively. Therefore, the facility layout during one period in the planning horizon can be obtained by solving the SFLP for each period. However, the flow data in whole planning horizon are changeable in DFLP. There exist rearrangement costs between the layouts for each pair of adjacent periods. That is to say, DFLP is composed of a series of SFLP if the rearrangement costs can be neglected. Therefore, DFLP involves selecting a SFLP for the first period and then deciding whether to change to a different SFLP in the next period. The dynamic layout shows flow dominance.

For each period, some departments have higher material handling inflows than the others. During the adjacent periods, if the higher material handling inflows do not change, the same SFLP will be used in these two periods. If these flow dominant departments change during the adjacent periods, changing to a different SFLP will occur in the following period.

For DFLP, the cycle of rearrangement depends on the rearrangement costs. If the rearrangement costs are relatively low, the layout configuration would tend to change more often to retain material handling efficiency. The reverse is also true for high rearrangement costs. The structural diagram of DFLP is given in Fig.5. Table 2 gives the comparison of main characteristics for SFLP and DFLP.

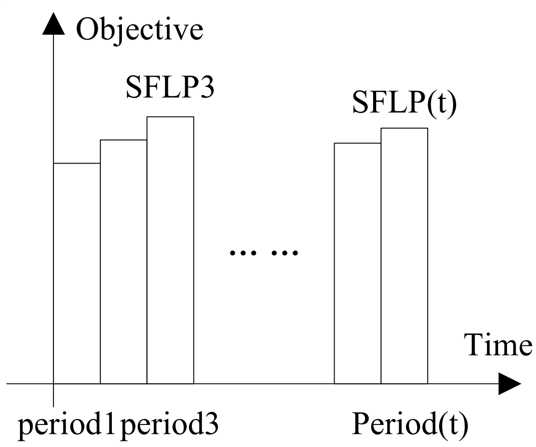

Fig. 5. Structural diagram of DFLP

	Period number	Rearrangement	Optimize objectives	Method for generating static layout of each period
SFLP	One period	No rearrangement	Minimize the material handling costs	The best static layout
DFLP	Multiple periods	Rearrangement costs	Minimize the material handling costs and rearrangement costs	The best static layout, or the random layout, or mixed layout*

*Mixed layout: combination of random layouts and the best layouts, each contributing half of the layout selected.

Table 2. Comparison between SFLP and DFLP

Objective Function of DFLP.

The objective function of a DFLP is generally defined as the minimization of the total costs, material handling costs for a series of SFLP plus rearrangement costs between periods. In each period, material handling costs among departments are calculated by the product of the probability of a flow matrix occurring in that period, the associated flows, and the distances. The formulation of the DFLP is given below.

$$\text{Min DFLP} = \sum_{t=1}^{T} \text{SFLP}(t) + \sum_{t=1}^{T-1} A_{t(t+1)} \tag{1}$$

where t is the number of periods in DFLP; $A_{t(t+1)}$ is the rearrangement costs between each pair of adjacent periods; and T is the total number of periods in the whole period horizon. Rearrangement costs are incurred when moving machines (or departments) from one location to another in order to minimize material handling costs in consecutive periods. Rearranging the layout will result in some shifting costs depending on the departments of the layouts. Rearranging includes the changes in location and orientation [5]. Each of the two aspects for facility will impact the total rearrangement costs. When the location and orientation of a facility in the new layout are the same as in the existing layout, no rearrangement cost is incurred for that facility. Otherwise, if the location or orientation of a facility has changed, then the specific facility rearrangement costs will be added to the objective function.

There are many approaches to calculate rearrangement costs for DFLP. Furthermore, the rearrangement of departments may lead to production loss, and it may also require specialized labor and equipment. Therefore, rearrangement costs consist of labor cost, equipment cost, out-of-pocket moving expenses and the cost of operational disruptions. Generally, the rearrangement (shifting) costs may be viewed as fixed costs, or a linear function of the distance between the various locations, or the linear function of square-feet being rearranged, or variable costs associated with moving a particular facility in a given period, or the accumulation of fixed costs due to changing in facility configuration, interrupting or disrupting production, using personnel and equipment to move the facility, or any combination of the above [5,6]. One special application of the DFLP is the rearrangement of existing facilities. In a rearrangement problem, the first period is the current SFLP and subsequent periods are the revised layouts.

Computation Complexity of DFLP.

As the SFLP, the DFLP is also the computationally intractable problem. In other words, the number of possible solutions or layout plans is $N!$ for a SFLP instance with N departments, while $(N!)^T$ for a DFLP instance with N departments and T periods. For this reason, with the same computer's configuration, only small problems can be optimally solved in reasonable computation time for DFLP while large and media problems can be solved for SFLP. The numbers of possible solutions and their methodologies for SFLP and DFLP are listed in Table 3.

For instance, even for a six-department, five-period problem, $(N!)^T$ is 1.93×1014 combinations. Thus for large problems obtaining optimal solutions is not nearly possible. So in practices, for small problem, $n=N!$; for large problem, $n<<N!$, where n is the number of static layout during each period in DFLP. n in each period depends on the capability of the software and hardware used to solve the DFLP. The more power these are, the larger n can be selected. Logically, larger n should lead to better solutions.

	Number of solutions	Size of problems	Methodologies
SFLP	$N!$	Small	Exact algorithm
		Media and large	Heuristic or meta-heuristic algorithm
DFLP	$(N!)^T$	Small and media	heuristic or meta-heuristic algorithm

Table 3. Numbers of solutions and methodologies for SFLP and DFLP

DFLP Degenerates into SFLP.

The SFLP has one period and no rearrangements, so it is just a special case of the DFLP. Under some conditions, DFLP may degenerate into SFLP. In those environments where material handling flows do not frequently change over a long time, SFLP analysis would be sufficient. When the rearrangement costs are negligible, dynamic layout analysis is not necessary. In the other cases, if the rearrangement costs are prohibitive, such as in the case of very heavy machinery, the same layout is used for the total planning horizon. In this situation, DFLP is also not necessary.

2.1.2 DFLP vs. robust layout

Robustness is defined as the frequency that a layout falls within a pre-specified percentage of the optimal solution for different sets of production scenarios [7]. For a robust layout, it is good for a wide variety of demand scenarios even though it may not be optimal under any specific demand scenarios. The objective of a robust layout is trying to minimize the total material handling costs over the specific planning horizon. Fig.6 illustrates the robust layout design framework [6].

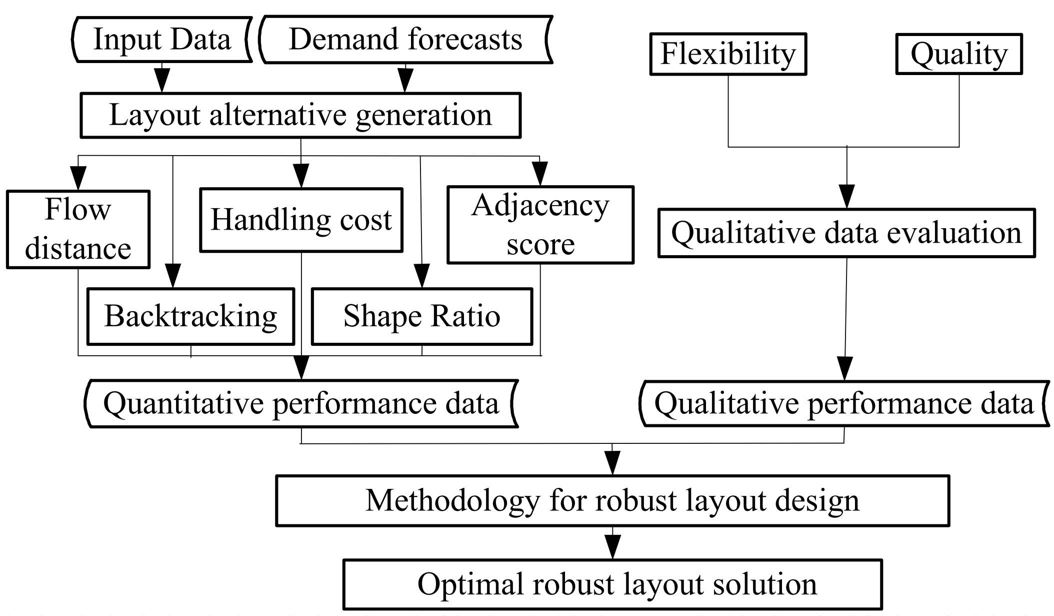

Fig. 6. Robust layout design framework

To some extent, robust layout is similar to SFLP. However, there is a difference between them: robust layout is researched under dynamic environment, and SFLP is assumed that the environment is static. Under the volatile environment, if the total planning horizon is divided into a lot of periods, DFLP is considered to be composed of a series of SFLP. Under some condition, if the number of periods is small over the planning horizon, *i.e.* each period has long time, DFLP is considered to be composed of a series of robust layout based on the definition of robust layout.

For DFLP, a set of planning time are referred to as a consecutive period with a layout rearrangement occurring only at the beginning of each period. The number and length of these periods are determined based on the trade-off between material handling costs and facility rearrangement costs. If rearrangement costs are larger than material handling costs, the number of these periods will be small and length will be long. The reverse is also true. Thus, the aim of DFLP is to modify the layout at the beginning of each period, but not to change the layout within these periods. In Contrast to DFLP, when rearrangement costs are extremely high, a pure robust layout will be selected, and it has the period equal to a total planning horizon. DFLP and robust layout are compared in Table 4. Robust layout will have different demand levels in the total planning horizon and will choose the demand level to minimize the material handling costs, adjacency scores and backtracking costs.

	Selective conditions	Period number	Function for material handling costs
DFLP	if production requirements change drastically and the rearrangement is easy	Multiple periods	Between the lower bound and upper bound on the expected material handling costs
Robust layout	if machine rearrangement costs are high	One period equal to the total planning horizon	Provide an upper bound on the expected material handling costs

Table 4. Comparison between DFLP and robust layout

As described in the last column of Table 4, robust layout provides an upper bound on the expected material handling costs while creating a new layout for each period provides a lower bound [8]. But in practical problems, creating a new layout for each period is unrealized. Therefore DFLP, which material handling costs are between the lower bound and upper bound, is necessary.

2.2 Discussions

The comparison among SFLP, DFLP and robust layout is presented in Table 5.

The fifth column of Table 5 refers the converting conditions of SFLP, DFLP and robust layout with each other. When the flows between department pairs are changeable, the SFLP will convert to DFLP or robust layout. When rearrangement costs are negligible, DFLP will convert to SFLP. However, when rearrangement costs are extremely high, DFLP will convert to robust layout. Under stochastic demand and when forecasting the future demand of products is difficult, robust layout will convert to DFLP. Since studies show that material handling costs make up 20-50% of the total operating costs and 15-70% of the total costs of manufacturing a product [9], the most common objective considered are the minimization of material handling costs. For DFLP, its objective function involves material handling costs and rearrangement costs. However, the objective of robust layout includes the total material handling costs for all product mix in total planning horizon.

The connection and difference between each pair of the types of layouts are described in Table 6.

Since assuming that the material handling flows are constant for SFLP, uncertainly of future production requirements are relatively low. DFLP is suitable for dynamic environment, so its uncertainty of future production requirements is high. Although SFLP and robust layout both have one period and no rearrangement, the application scopes are different-one for static environment and the other for dynamic environment. DFLP and robust layout are both used under the dynamic and changeable environment, but DFLP considers the rearrangement and robust layout does not consider for only using one facility layout solution during the whole planning horizon.

	Application scope	Advantages	Disadvantages	Converting condition	Objective function
SFLP	Flows between pairs of departments do not change over a long time	Widely used; low computational complexity; modeling easily	Flows between departments are assumed to be constant over time	Flows between department pairs are changeable	$\min \sum_{i=1}^{n} \sum_{j=1}^{n} c_{ij} f_{ij} d_{ij}$ $i, j = 1, 2, ..., n$
DFLP	The relative material flows between departments change over time	Moving expenses and operational disruption	High computational complexity	Rearrangement costs are either negligible or extremely high	$\min(\sum_{t=1}^{P} \sum_{i=1}^{n} \sum_{j=1}^{n} \sum_{k=1}^{n} \sum_{l=1}^{n} f_{tij} d_{tij} X_{t}$ $+ \sum_{i=1}^{t-1} A_{t(t+1)})$
Robust Layout	Under stochastic demand and the re-layout is prohibited	Offer low mean and variance in distance traveled; lower material handling costs over large changes in product demand	It is not the best optimal solution for a special product.	Forecasting the future demand of products is difficult	$\min \sum_{m=1}^{M} \sum_{i=1}^{n} \sum_{j=1}^{n} C_{mij} f_{mij} d_{m}$ $i, j = 1, 2, ..., n$; m product mix

Table 5. Comparison among SFLP, DFLP and robust layout

<table>
<tr><th></th><th>SFLP</th><th>DFLP</th><th>SFLP</th><th>Robust layout</th><th>DFLP</th><th>Robust layout</th></tr>
<tr><td>Connection</td><td colspan="2">SFLP is the base and the special case of DFLP</td><td colspan="2">One period and no rearrangement</td><td colspan="2">In the dynamic and changeable environment</td></tr>
<tr><td rowspan="2">Difference</td><td colspan="2">Uncertainty of future production requirements</td><td rowspan="2">Static environment</td><td rowspan="2">Dynamic environment</td><td rowspan="2">Multiple periods and rearrangement</td><td rowspan="2">One period and no rearrangement</td></tr>
<tr><td>Low</td><td>High</td></tr>
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Table 6. Connection and difference between each pair of the types of layouts

2.3 Summaries

In this part, the relationship among SFLP, DFLP and robust layout are researched. The characteristics of SFLP, DFLP are analyzed first. Then DFLP and robust layout are compared. The research results are given as followings:

1. The application scope of DFLP is different from SFLP and robust layout.

2. DFLP can convert to SFLP or robust layout in some conditions.
3. Among SFLP, DFLP and robust layout, the majority of practical problems will be classified to DFLP.
4. SFLP is the base of DFLP and robust layout.
5. SFLP and robust layout both are the special case of DFLP.

3. Objectives and constraints of FLP

The facility layout problem, block layout, considers the assignment of facilities to locations so that the quantitative (qualitative) objective of the problem is minimized (maximized) under various constrains.

3.1 Objectives of FLP

Traditionally, there are two basic types of objectives for FLP [10]. The first one is the quantitative (distance-based) objective aiming at minimizing the total material handling cost between departments based on a distance function. The distance-based objective, considers all distance pairs, but due to department areas, inter-department distances may be misleading. To help relieve this concern, distances have been measured in a variety of ways: from department centroid-to-centroid, expected distance, distance from department boundaries, distance along the material handling network, etc. Even so, since the choice between general-purpose and special-purpose material handling devices may depend on whether or not departments are adjacent, the same inter-department distance may not have the same material handling cost.

In general, the actual cost to move a unit load of material between two departments will be the sum of a fixed cost and a variable cost. The fixed cost is dependent on the waiting time to obtain the appropriate material handling method, the time to pickup and deposit the unit load, and possibly some charge for the initial purchase cost of the material handling method. The variable material handling cost is dependent on the distance the unit load travels. In single-floor facilities this has a near-linear relation, while in multi-floor facilities it is a non-linear relationship.

The second one is the qualitative (adjacency-based) goal, aimed at maximizing the closeness relationship scores between departments based on the placement of departments that utilize common materials, personnel, or utilities adjacent to one another, while separating departments for reasons of safety, noise, or cleanliness. The adjacency-based objective, if interpreted from a material handling cost perspective, is based on the assumption that the material handling costs between two departments are reduced significantly when the two departments are adjacent. The adjacency-based objective appears to assume that fixed costs dominate the total costs (to the extent we can ignore the variable material handling costs) and that more efficient (and less costly) material handling methods may be used when departments are adjacent. On the other hand, the distance-based objective models the variable material handling costs and ignores the fixed costs.

Over the years, extensive research has been conducted on FLP. Yet, most of the research conducted in this field has concerned a single objective, either qualitative or quantitative goodness of the layout. In general, minimization of the total material handling costs is often used as the optimization criterion in FLP. However, closeness, hazardous movement or safety, and similar criteria are also important in FLP. Inherently, real-life layout problems are multi-objective by nature and the FLP must consider both quantitative and qualitative objectives simultaneously. Consequently, FLP falls into the category of multi-objective optimization problem.

3.2 Constraints of FLP

Facility layout plays a crucial role in determining the throughout time of a manufacturing process. The objective of the facility layout problem in manufacturing environment is the arrangement of facilities on a floor shop [11], subject to the following constraints:

1. to reduce the flows among all facilities;
2. to have a regular flow of the parts and products not permitting bottleneck in the production;
3. to rationalize the space occupied by the facilities;
4. to permit flexibility considering that with the technological progress and the new demands in the market, facilities could be added or changed.
5. to locate in a specified location.

Facilities are including machines, departments, storage equipments, factory, material-handling systems, commerce and warehouse. In the manufacturing system it may be distinguished machines, material handling systems and storage equipments.

4. Mathematic formulation of facility layout problem

For the past decades researchers have been working on facility layout problem while considering various aspects which vary with the nature of production demand, shape of the facilities, number of floors, and nature of material flow. Despite these variations, the process of obtaining optimal solutions involves two steps: modeling the facility layout problem, and developing a solution approach. Modeling helps clearly define the problem and consider the factors that are imperative in developing layouts.

The facility layout problem is one of the best-studied problems in the field of combinatorial optimization. A number of formulations have been developed for this problem. Models are categorized depending on their nature, assumptions and objectives. More particularly the FLP has been modeled as quadratic assignment problem (QAP), quadratic set covering problem (QSP), linear integer programming problem (LIP), mixed integer programming problem (MIP), and graph theoretic problem.

4.1 Quadratic assignment problem (QAP)

Koopmans and Beckman were the first to model the problem of locating plants with material flow between them as a quadratic assignment problem (QAP) in 1957 [12]. The name was so given because the objective function is a second-degree function of the variables and the constraints are linear functions of the variables. More specifically, it is an NP-hard problem and one of frequently used formulation to solve FLP.

Consider the FLP of allocating a set of facilities to a set of locations, with the objective to minimize the cost associated not only with the distance between locations but with the flow also. Each location can be assigned to only one facility, and each facility can be assigned to only one location. There is material flow between the different departments and cost (material handling) associated with the unit flow per unit distance. Thus, different layouts have different total material handling costs depending on the relative location of the facilities. F_{ik} is the flow between facilities i and k, and D_{jl} is the distance between location j and l. The FLP has been formulated as follows:

$$\sum_{\substack{i=1 \\ i\neq k}}^{n}\sum_{\substack{j=1 \\ j\neq l}}^{n}\sum_{k=1}^{n}\sum_{l=1}^{n} F_{ik} * D_{jl} * X_{ij} * X_{kl} \tag{2}$$

$$s.t.\ \sum_{i=1}^{n} X_{ij} = 1 \qquad \forall\ j = 1,\ldots,n \tag{3}$$

$$\sum_{j=1}^{n} X_{ij} = 1 \qquad \forall\ i = 1,\ldots,n \tag{4}$$

$$X_{ij} \in \{0,1\} \qquad \forall\ i,j = 1,\ldots,n \tag{5}$$

$X_{ij} = 1$ if facility i is assigned to location j and $X_{ij} = 0$ if facility is not assigned to location j, where n is the number of facilities. Equation (2) seeks to minimize the sum of flow multiplied by the distance for all pairs of facilities in a given layout. Equation (3) ensures that each location contains only one facility while equation (4) ensures that each facility is assigned to only one location.

4.2 Quadratic set covering problem (QSP)

Bazaraa formulated facility layout problem as a quadratic set covering model in 1975 [13]. In this formulation, the total area occupied by all facilities is divided into a number of blocks where each facility is assigned to exactly one location and each block is occupied by at most one facility. The distance between the locations is taken to be from centriods of the locations and the flow between facilities is minimized. The disadvantage of this approach is that the problem size increases as the total area occupied by all the facilities is divided into smaller blocks.

4.3 Linear integer programming problems (LIP)

Several integer programming formulations have been proposed for the facilities layout problem. Lawler was the first one to formulate the FLP as a linear integer programming model [14]. He proved that his model is equivalent to QAP. QAP has n^2 k_{ij} variables and $2n$ constraints while integer programming problem has n^4+2n+1 constrains and n^4 Y_{ijkl} while n is the number of locations, X_{ij} is the integer variable of facility i at location j, and Y_{ijkl} is the integer variable of facility i at location j in arrangement k of location l.

Assumption $y_{ijkl} = x_{ij} \cdot x_{kl}$

$$\text{Min}\sum_{i=1}^{n}\sum_{j=1}^{n}\sum_{k=1}^{n}\sum_{l=1}^{n} b_{ijkl}\, y_{ijkl} \tag{6}$$

$$s.t. \quad \sum_{j=1}^{n} x_{ij} = 1,\ i = 1,2,\ldots,n; \tag{7}$$

$$\sum_{i=1}^{n} x_{ij} = 1 \quad j = 1,2,\ldots,n; \tag{8}$$

$$\sum_{i=1}^{n}\sum_{j=1}^{n}\sum_{k=1}^{n}\sum_{l=1}^{n} y_{ijkl} = n^2 \tag{9}$$

$$x_{ij} + x_{kl} - 2y_{ijkl} \ge 0\ i,j,k,l = 1,2,\ldots,n \tag{10}$$

$$x_{ij} \in \{0,1\} \quad i,j = 1,2,\ldots,n. \tag{11}$$

$$y_{ijkl} \in \{0,1\}\ i,j,k,l = 1,2,\ldots,n \tag{12}$$

$$b_{ijkl} = \begin{cases} f_{ik}c_{jl} + a_{ij} & i = k,\, j = l \\ f_{ik}c_{jl} & i \ne k \ \ or \ \ j \ne l \end{cases} \tag{13}$$

4.4 Mixed integer programming problems (MIP)

Kaufman and Broeckx developed a linear mixed integer programming model in 1979 [15], which has the smallest number of variables and constraints among all integer programming formulations of the QAP. The equivalence between QAP and the mixed integer programming has been proposed through this model.

Assumption $w_{ij} = x_{ij}\sum_{k=1}^{n}\sum_{l=1}^{n} b_{ijkl}x_{kl}$, $e_{ij} = \sum_{k=1}^{n}\sum_{l=1}^{n} b_{ijkl}$

$$\text{Min}\sum_{i=1}^{n}\sum_{j=1}^{n}\sum_{k=1}^{n}\sum_{l=1}^{n} b_{ijkl}x_{ij}x_{kl} = \sum_{i=1}^{n}\sum_{j=1}^{n} x_{ij}\left(\sum_{k=1}^{n}\sum_{l=1}^{n} b_{ijkl}x_{kl}\right) = \sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij} \tag{14}$$

$$s.t \ \sum_{j=1}^{n} x_{ij} = 1 \ \ i = 1,2,\ldots,n;, \tag{15}$$

$$\sum_{i=1}^{n} x_{ij} = 1 \quad j = 1,2,\ldots,n;, \tag{16}$$

$$e_{ij}x_{ij} + \sum_{k=1}^{n}\sum_{l=1}^{n} b_{ijkl}x_{kl} - w_{ij} \le e_{ij} \tag{17}$$

$$w_{ij} \geq 0 \quad i, j = 1, 2, \ldots, n. \tag{18}$$

$$x_{ij} \in \{0,1\} \quad i, j = 1, 2, \ldots, n. \tag{19}$$

4.5 Graph theoretic formulations

In graph theoretic formulations it is assumed that the desirability of locating each pair of facilities adjacent to each other is known [16]. In this model a closeness rating indicating desirability of locating facility i adjacent to facility j is assumed. The model seeks to maximize the closeness rating of the facilities.

5. Solution methodologies for facility layout problem

Several researches have been done in the facility layout problem. The solution methodologies for FLP can be divided into exact algorithms, heuristics and meta-heuristic algorithms [17]. The exact methods such as the branch-and-bound and cutting plane algorithm have been successfully applied to FLP when the number of facilities is less than 16. However, when the number of facilities is larger than 16, FLP cannot be solved optimally in reasonable time. In order to obtain good (near optimal) solution in a reasonable computational time, heuristics were developed. Recently, meta-heuristic approaches such as simulated annealing (SA), genetic algorithms (GA), tabu search (TS), and colony optimization have been successfully applied to solve large FLP.

5.1 Exact algorithms

Exact algorithms are clever version of exhaustive search approach. Branch-and-bound and cutting plane algorithms are used to solve the FLP modeled as QAP optimally. These exact algorithms are complete in the sense that the existence of a feasible solution and then the optimal solution can be determined with certainty once such exact algorithm is successfully terminated. The main disadvantage of these exact algorithms is that they entail heavy computational requirements when applied even to small size problems.

5.1.1 Branch and bound algorithms

Branch and bound methods are used to find an optimum solution of quadratic assignment formulated FLP because QAP involves only binary variables. In branch and bound algorithms, the solution procedure proceed on the basis of stage by stage or parallel search of single assignment or pairs of assignments of facilities to locations. At each stage back tracking occurs, certain assignments are excluded and the forward search process is resumed.

Only optimal solutions up to a problem size of 16 are reported in literature. Beyond n=16 it becomes intractable for a computer to solve it and, consequently, even a powerful computer can not handle a large instance of the problem.

5.1.2 Cutting plane algorithms

Cutting plane methods are exact algorithms for integer programming problems. They have proven to be very useful computationally in the last few years, especially when combined with a branch and bound algorithm in a branch and cut framework. Cutting plane algorithms work by solving a sequence of linear programming relaxations of the integer programming problem. The relaxations are gradually improved to give better approximations to the integer programming problem, at least in the neighborhood of the optimal solution. For hard instances that can not be solved optimality, cutting plane algorithms can produce approximations to the optimal solution in moderate computation times, with guarantees on the distance to optimality.

5.2 Heuristic algorithms

In order to obtain good (near optimal) solution in a reasonable computational time, heuristic algorithms were developed [18]. A heuristic algorithm can be defined as a well-defined set of steps for quickly identifying good quality solutions. The quality of a solution is defined by an evaluation criterion, e.g., minimize material handling cost, and the solution must satisfy the problem constraints. Basically, heuristic algorithms for FLP can be classified into four classes: construction algorithms, improvement algorithms, hybrid algorithms and graph theoretic algorithms.

5.2.1 Construction algorithms

Construction algorithms are considered to be the simplest and oldest heuristic approaches to solve the QAP, from a conceptual and an implementation point of view. A construction algorithm consists of successive selection and placement of facilities until a complete layout is achieved. These methods are probably the oldest ones, dating back to the early 60s. The simplicity of construction algorithm is often associated with poor quality of the resulting solutions.

But these construction algorithms can be used to provide initial solutions for improvement algorithms. Improvement methods start with a feasible solution and try to improve it by interchanges of single assignments.

5.2.2 Improvement algorithms

An improvement algorithm starts with an initial solution (existing layout). This existing layout is improved by exchanging the locations of a pair of facilities. The exchange, which produces the best solution, is retained and the procedure continues until the solution cannot be improved any further or until a stopping criterion is reached. Hence, the solution quality of improvement algorithms greatly depends on the initial layout provided, and the systematic procedure of the location exchange.

The greedy nature of pair-wise exchange makes it susceptible to converge to a local optimum. Therefore, the shortcomings of improvement algorithms originate not only from the initial solution provided but also from the greedy nature of the systematic exchange procedure. The greedy nature of the procedure is exposed because only the location exchanges, which result in the greatest cost reduction, are accepted. Hence, the nature of the exchange procedure often impedes the algorithm from finding the global optimum and causes the algorithm to converge to a local optimum.

Improvement methods can easily be combined with construction methods.

Improvement algorithms can be meta-heuristic such as SA and TS, which require one feasible solution as starting solution for the execution of these algorithms.

5.2.3 Hybrid algorithms

In hybrid algorithms the solution of QAP is determined by using a combination of two optimal or sub-optimal algorithms. Such combination of algorithms is essential in some cases to improve solution quality. This classification is extended to include certain algorithms, which use the principal of construction algorithms and improvement algorithms. FLAC and DISCON are examples of such hybrid algorithms.

5.2.4 Graph theoretic algorithms

Graph theoretic algorithms identify maximal planar subgroups of a weighted graph that show the relationships between the facilities [19]. The dual of a maximal planar sub graph determines the layout of the facilities. Seppanen and Moore proposed graph theoretic solutions procedure in which a heuristic algorithm, which uses this strategy, was also presented. The algorithm determines the maximum spanning tree based on the weighted graph. With the help of one edge adding process, the maximum spanning tree is the used to obtain a maximal planar sub graph. The dual of the maximal planar sub graph determines a layout of the facilities.

5.3 Meta-heuristic algorithms

The development of meta-heuristic algorithms has greatly influenced the performance of improvement algorithm and uses a general strategy like pair-wise exchange heuristic. There are three classes widely used of meta-heuristic algorithms in layout problem i.e. Simulated annealing (SA), tabu search (TS), and genetic algorithms (GA).

5.3.1 Simulated annealing algorithms (SA)

Simulated annealing (SA) is a general probabilistic local search algorithm, proposed by Kirkpatrick et al in 1983, to solve difficult optimization problems. Many large instances of difficult real life problems were successfully solved by simulated annealing algorithms. Its ease of implementation, convergence properties and its use of hill-climbing moves to escape local optima has made it a popular technique over two decades. SA is based on the analogy between the annealing of solids and the solving of combinatorial optimization problems [20]. SA is a step-by-step method which could be considered as an improvement of the local optimization algorithm. This process accepts not only better solutions but also worse solutions with a certain probability which is called the probability of accepting. The probability of accepting is determined by the temperature. The probability of accepting a worse solution is large at a higher temperature. As the temperature decreases, the probability of accepting a worse solution also decreases as well.

SA has advantages and disadvantages compared to other global optimization techniques, such as genetic algorithms, tabu search algorithms, and neural networks algorithms. Among its advantages are the relative ease of implementation and the ability to provide reasonably good solutions for many combinatorial problems. Though a robust technique, its drawbacks include the need for a great deal of computer time for many runs and carefully chosen tunable parameters.

5.3.2 Genetic algorithms (GA)

Genetic algorithms (GA) is a heuristic search that mimics the process of natural evolution, which encode a potential solution to a specific problem on a simple chromosome-like data structure and apply operators like mutation, recombination to create new data strings and to preserve critical information [21,22].

GA gained more attention during the last decade than any other evolutionary computation algorithms; it utilizes a binary coding of individuals as fixed-length strings over the alphabet {0, 1}.

Evolution, or more specifically biological evolution, is the change over time in one or more inherited traits of individuals. Natural selection, genetic drift, mutation, gene flow are the four corresponding common mechanisms of evolution. After a long enough time, only the adaptive individuals survive as a consequence of natural selection. To put it concisely, whether the individual should survive or not is decided by two factors, the gene in the individual and the fitness of the gene in the whole population. Mimicking the mechanism, genetic algorithm applies as a searching tool finding out the fittest individuals among a population. More often, the algorithm is viewed as a function optimizer, implementing first by defining two attributes of the individuals: the gene (a data string specifies the individual's character) and the fitness (a function evaluates the individual's vitality). Thus, the two main components of most genetic algorithms that are problem dependent are: the problem encoding (the gene of the individual) and the evaluation function (the fitness). Subsequently, certain operators like mutation and recombination are applied to select the fittest offspring after several generations as the finial individuals, the corresponding optimal answer to the problem when decoded.

GA iteratively search the global optimum, without exhausting the solution space, in a parallel process starting from a small set of feasible solutions and generating the new solutions in some random fashion.

5.3.3 Tabu search algorithms (TS)

Tabu search (TS) was proposed by Glover and has quickly become one of the most effective methods using local search techniques to find near-optimal solution to combinatorial optimization problems. It uses a deterministic local search technique which is able to escape local optima by using a list of prohibited neighbor solutions known as the tabu list. In addition to escaping local optima, using the tabu list can also prevent cycling by forbidding or penalizing moves which take the solution, in the next iteration, to points in the solution space previously visited, and thus save computational time.

A drawback of tabu search is that if it reaches a previously visited solution, it will cycle following the same path unless a tabu neighbor exists. In other words, if the search moves to a previously visited solution that has not been tabu for the last two iterations, then a loop is encountered.

5.3.4 Ant colony algorithms (ACO)

Recently, a few papers have appeared where an ant colony algorithm (ACO) has been attempted to solve large FLP. The first ACO system was introduced by Marco Dorigo in his Ph.D. thesis in 1992, and was called ant system.

ACO is a heuristic search technique to seek for an optimal path in a graph, inspired by the ability of ants to find food sources by using a substance called pheromone. Ant belongs to a colony leave the nest and randomly search for a food source. When an ant finds a food source, it returns to the nest to let others know about the source. On the way back to the nest, the ant places pheromone, which ants are sensitive to, to mark the path from the food source to the nest. Ants select their path to food sources according to the pheromone concentration on different paths. Pheromone evaporates over time, and this causes less frequently visited food sources to lose their address hence to be less visited by others ants. This mechanism has been the cornerstone to devise meta-heuristic algorithms for finding good solutions for difficult optimization problems.

5.4 Other approaches

The major drawbacks of the aforementioned approaches lie in the fact that the search for the best layout is not very efficient and the multi-objective nature are not considered in the problem. As a matter of fact, facility layout problem can be considered one of the truly difficult ill-structured, multi-criteria and combinatorial optimization problems. Many researchers still finding out for new and recent developments rather than conventional approaches to overcome the aforementioned drawbacks. Intelligent techniques such as expert systems, fuzzy logic and neural networks have been used as new advancements for the tackled problem.

6. Computer simulations

The typical absence of some encompassing, closed-form, and analytical fitness functions renders computer simulations a useful alternative. Such an approach would provide detailed analysis, modeling, and evaluation of complex layout design problems. However, simulation models are not easily amenable to optimization and make procurement of a superior layout alternative difficult to achieve. Recently, some efforts have been made to optimize layout design simulation models using genetic algorithms in various facility layout design contexts in order to expedite the process and procure a diverse set of superior in layout alternatives. Nevertheless, computer simulations are usually very time consuming and could become prohibitive in the facility layout design process.

7. Facility layout based on manufacturing costs

Facility layout is composed of product, its process routing, machine and some space. Different combinations of these entities and their activities affect the type of facility layout. Considering the criteria of material handling route, the types of facility layout are classified into three types: single-row layout, multi-row layout and loop layout, as shown in Fig. 6. The application scope, advantages and disadvantages are illustrated in Table 7. The single-row layout includes three shapes such as linear, U-shape and semi-circular. In the linear layout, there may exist bypassing and backtracking, as shown in Fig. 1(a). Backtracking is the movement of some parts from a machine to another machine that precedes it in the sequence of placed machines in a flow line arrangement. Bypassing occurs when a part skips some machines while it is moving towards the end of a flow line arrangement. Table 8 gives the comparison of main characteristics for backtracking and bypassing.

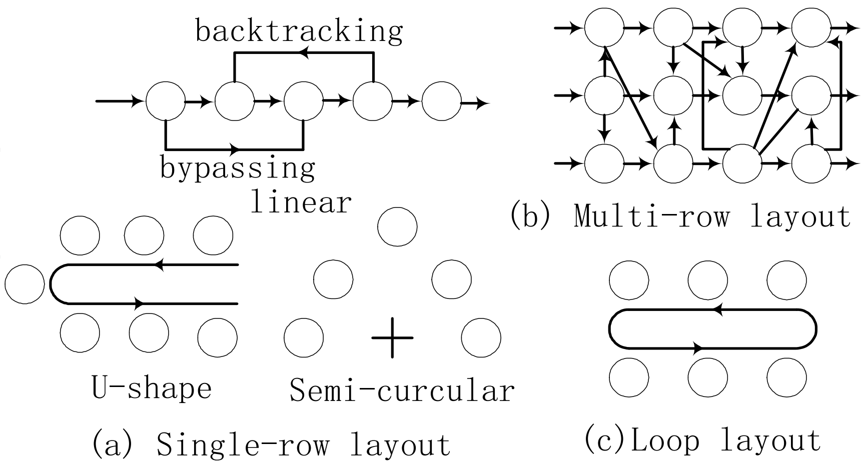

Fig. 6. Types of facility layout based on the criteria of material handling route

Type of layout		Application scope	Advantages	Disadvantages
Single-row layout	Linear	Within GT cells, in facilities that implement JIT, and sometimes with FMS	Material flow are moving along the sequence of operations of all the parts; small material handling cost and time; less delays; better control of operations; the ability to use conveyors.	When several parts having different sequence of operations are processed, the benefits of a flow line arrangement are reduced since the movement of parts may not always be unidirectional.
	U-shape			
	Semi-circular			
Multi-row layout		Suitable for FMS	Adjacent lines share common equipments; low investment; small space area; high machine utilization rate;	Complicated process management; coordinate multi-task difficulty.
Loop layout		Used in FMS	High flexibility in material handling system	

Table 7. Comparison of three types of layout

	Direction	Derivation	Disadvantages	Objective	Scope
Backtracking	Adverse sequence of operations in the flow line	The difference in the sequences of operations of the parts	Impacts the movement cost and productivity of facility	Should be minimize.	In traditional facilities
Bypassing	Same sequence of operations in the flow line	The same with above.	Unnecessary travel time and cost	The same with above	The same with above.

Table 8. Comparison of backtracking and bypassing

7.1 Problem statement

Selling price of products is the concerned problem for customers. Therefore how to decrease the selling price by effective layout planning is an important issue.

7.1.1 Manufacturing cost

Skinner provides the breakdown of costs for a manufacturing product [17], shown in Fig. 7. About 40% of the selling price of a product is manufacturing cost. Material and parts make up the largest percentage of total manufacturing cost, at round 50%. Direct labor is responsible for operating the facilities and is a relatively small proportion of total manufacturing cost: 12%. It is only about 5% of selling price. Machinery, plant and energy etc. are about 26% of manufacturing cost. Therefore, decreasing the manufacturing cost is the key to lower the selling price of products.

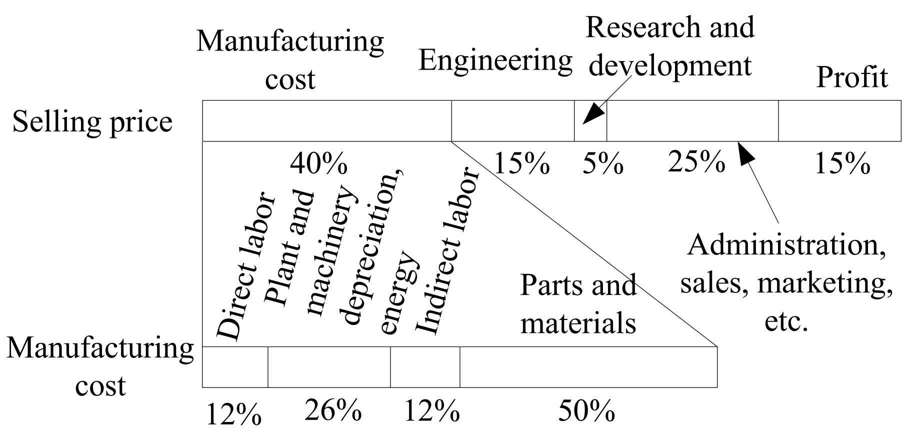

Fig. 7. Breakdown of costs for a manufactured product

Manufacturing cost has two classify methods. The first one classifies the manufacturing cost into fixed costs and variable costs. The second separates manufacturing cost into: (1) direct labor, (2) material, and (3) overhead. In this chapter, the second one is selected. The classification of manufacturing cost is shown in Fig. 8. The direct labor cost is the sum of the wages and benefits paid to the direct labor. The smaller the number of direct labor, the lower the manufacturing cost. The material cost is the cost of all raw material used to manufacture the parts or products. Overhead costs are all of the other expenses associated with running the manufacturing firm. Overhead divides into two categories: (1) factory overhead and (2) corporate overhead. Detail expenses of overhead costs are listed in Table 9.

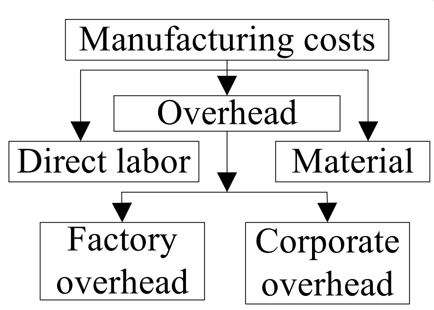

Fig. 8. Classification of manufacturing cost

Factory overhead costs		Corporate overhead costs	
Plant supervision	Applicable taxes	Corporate executives	Applicable taxes
Line foreman	Insurance	Sales and marketing	Cost of space
Maintenance crew	Heat and air conditioning	Accounting department	Security personnel
Custodial services	Light	Finance department	Heat and air conditioning
Security personnel	Power for machinery	Legal counsel	Light
Tool crib attendant	Factory depreciation	Engineering	Insurance
Material handling	Equipment depreciation	Research and development	Fringe benefits
Shipping and receiving	Fringe benefits	Other support personnel	Other office costs

Table 9. Typical overhead costs

Factory overhead consists of the costs of operating the factory other than direct labor and materials. Corporate overhead is the cost of running the company other than its manufacturing activities. As shown in Table 9, material handling cost in factory overhead and cost of space in corporate overhead are the two parts which relate to the facility layout. When material handling cost and cost of office space increase, the manufacturing cost increase accordingly.

7.1.2 Objectives of facility layout based on manufacturing cost

Groover observes that materials spend more time waiting or handling than in process [23]. His observation is illustrated in Fig. 9. Only 5% of the time is spent on the machine. About 95% of a part's time is spent either moving or waiting. This figure shows that the material handling and storage are significance in a typical factory. Furthermore, studies show that material handling cost makes up 20%-50% of the total operating cost and 15%-70% of the total manufacturing cost. Therefore, the most common objective of facility layout is the minimization of material handling cost.

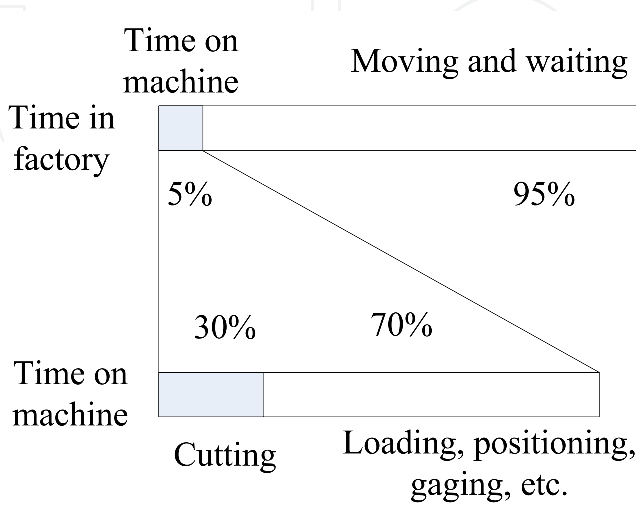

Fig. 9. How time is spent by a typical part in batch production machine shop

When the cost of space increases, the manufacturing cost increase accordingly. With the given purchase price of unit space area, the higher the area utilization rate is, the lower the manufacturing cost is. So, one objective of facility layout is to maximize the area utilization rate.

Combination of the Fig. 7 and 8 show that other than materials and parts, direct labor and machinery are main parts of manufacturing cost. The higher the utilization rate of direct labor and machinery are, the lower the manufacturing cost is. Increased utilization of existing machinery could lead to smaller machine inventories since less machinery would be sitting unused, and the direct labor are the same. Hence the maximization of the utilization rate of direct labor and machinery are also the objective of facility layout.

To sum up, the objectives of facility layout based on manufacturing cost include: (1) minimizing the material handling cost, (2) maximizing the area utilization rate, and (3) maximizing the utilization rate of direct labor and machinery.

7.2 Model formulation

7.2.1 Material handling cost

For manufacturing facilities, material handling cost is the most significant measure for determining the efficiency of a layout and is most often considered. It is determined based on the flows of materials between departments and the distances between the locations of the departments. The material handling cost model has the following form:

$$F = \sum_{i=1}^{n}\sum_{j=1}^{n} c_{ij} f_{ij} d_{ij} \qquad i, j = 1, 2, \ldots, n \tag{20}$$

Note that c_{ij} is the unit cost (the cost to move one unit load one distance from department i to j), f_{ij} is the material flow between the department i and j, d_{ij} is the distance between the centers of department i and j.

7.2.2 Area utilization rate

Area utilization rate of whole layout is a ratio of total areas required of all facilities to the smallest possible rectangle, which can envelop all the facilities [24]. Hence, the area utilization area rate of whole layout is shown as follow:

$$R_s = \frac{\sum_{i=1}^{n} A_i}{\sum_{i=1}^{n} A_i + \sum B_j} \times 100\% \tag{21}$$

Note that R_s is the Area utilization rate, A_i is the area of department i where equipment i is sitting, B_j is the blank area of layout.

7.2.3 Equipment utilization

Up to now, there exist three views about equipment utilization. Østbye defines that equipment utilization is measured as of the ratio of the number of units reported in use by the surveyor relative to the total number of units recorded as present by the surveyor [25]. This measure was calculated daily, for both the intervention and control wards, during the pre- and post-intervention control periods as well as the intervention period. Optimal efficiency of utilization would have a ratio of 1, indicating that every unit present was in use. Increased utilization of existing equipment could lead to smaller equipment inventories since less equipment would be sitting unused. Michael Vineyard thinks that equipment utilization measures the percentage of time the machines are in use and considers factors beyond just maintenance downtime [26]. Steege puts forward that equipment utilization has three affecting factor: rate of quality, availability and performance efficiency [27]. Rate of quality measures the percentage of defect-free product that is manufactured by a piece of equipment. It determines the effect of the equipment on product yield. It is equally significant from a productivity point of view whether or not the equipment is running at full capacity. Equipment availability measures the percentage of time that equipment is ready to perform its manufacturing function. Performance efficiency is the percentage of available time that equipment is producing sellable product.

In this chapter, performance efficiency is selected to evaluate the equipment utilization. The equipment utilization affected by performance efficiency can be formally stated as follow:

$$R_{EU} = \frac{T_O}{T_A} \times 100\% \tag{22}$$

Note that R_{EU} is equipment utilization, T_O is the operation time of equipment, including processing time, unload time, and setup time, T_A is the available time of equipment.

7.2.4 Labor utilization

Labor utilization measures as average hours worked through overtime work (and possibly short-time work) [28]. The optimal labor utilization, i.e. hours worked per employee is explained by average wage rates which are functions of the hours worked [29]. Thus, Average labor utilization of layout can be written as:

$$R_L = \frac{T_W}{T_T} \times 100\% \tag{23}$$

Note that R_L is average labor utilization, T_W is the work time of labor, including processing, loading, unloading, loaded and empty travel time, T_T is the total time of labor in a factory.

7.3 Simulation and results

The simulation was carried out in Deneb/QUEST platform in order to investigate the performance of three types of facility layout. QUEST is a discrete event simulation software package, used to model and simulate the operation of complex automated manufacturing systems. Using 3D CAD geometry, QUEST analyzes the performance of existing or proposed manufacturing facilities by simulating the process behavior over a specified time. QUEST combines a graphical user interface with material flow logic grouped in modules for: labor, conveyors, automated guided vehicles (AGVs), kinematics, power and free conveyors, and automated storage and retrieval systems (AS/RS). A Value-Added Costing module assists in implementation of Activity Based Costing during the simulation analysis, Statistical results can be viewed with graphical and numerical analysis capabilities.

The piston production line-117 is chosen as an example to simulate. The simulation procedure is illustrated in Fig. 10. Virtual facility model can be gain from the equipment database of QUEST. The process parameters of piston are inputted to QUEST through process DB. Logic and algorithm DB provide rules and procedures that govern the behavior of the element and algorithm for the simulation system. At the final of this procedure, QUEST supplies simulation data to user in order to analysis the three types of facility layout.

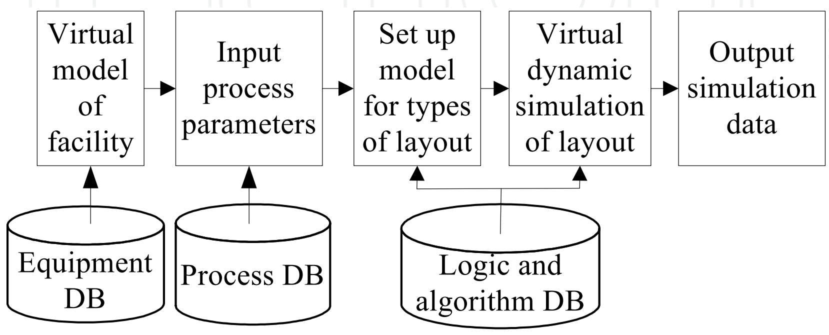

Fig. 10. Simulation procedure of facility layout

7.3.1 Assumptions and constrains

Two major assumptions made in the proposed models are as follows: (1) Machines are rectangular with the same dimensions and the distance between the machines is calculated with respect to their centers. (2) The clearance between each pair of machines is fixed.

For three types of facility layout, two set of constrains are considered: (1) one machine is assigned to each location and each machine is assign to only one location; (2) the clearance between each pair of macines has the minimal value to avoid intervening and overlapping with each other.

Based on assumptions and constrains, the simulation models of the facility layout described above are given in Fig. 11.

7.3.2 Simulation results and analysis

The man-hour arrangement of piston production line is listed in Table 10. Quantity represents the number of machines. Setting the simulation time is one work day, i.e. 6.5 hours. The loaded travel time is measured by minute. Setting the moving velocity of labor is 304mm/sec and c_{ij} is 1. The simulation results are compared in Table 11~14.

The simulation results listed in Table 11 show that the material handling cost of loop layout is the lowest, and multi-line layout is the highest due to the distances between the centers of departments in which the materials are handled. As for area utilization rate shown in Table 12, loop layout is higher than the others, and semi-circular layout is the lowest of the three types of facility layout as a result of the blank areas of it is the largest. The results in Fig. 7 show that the equipment utilization of U-shape layout is the higher than others in the same moment. At aspect of labor utilization presented in Fig. 8, the U-shape layout is better than the others, and linear layout is the worst owing to the sum of its hanling materials is minimum.

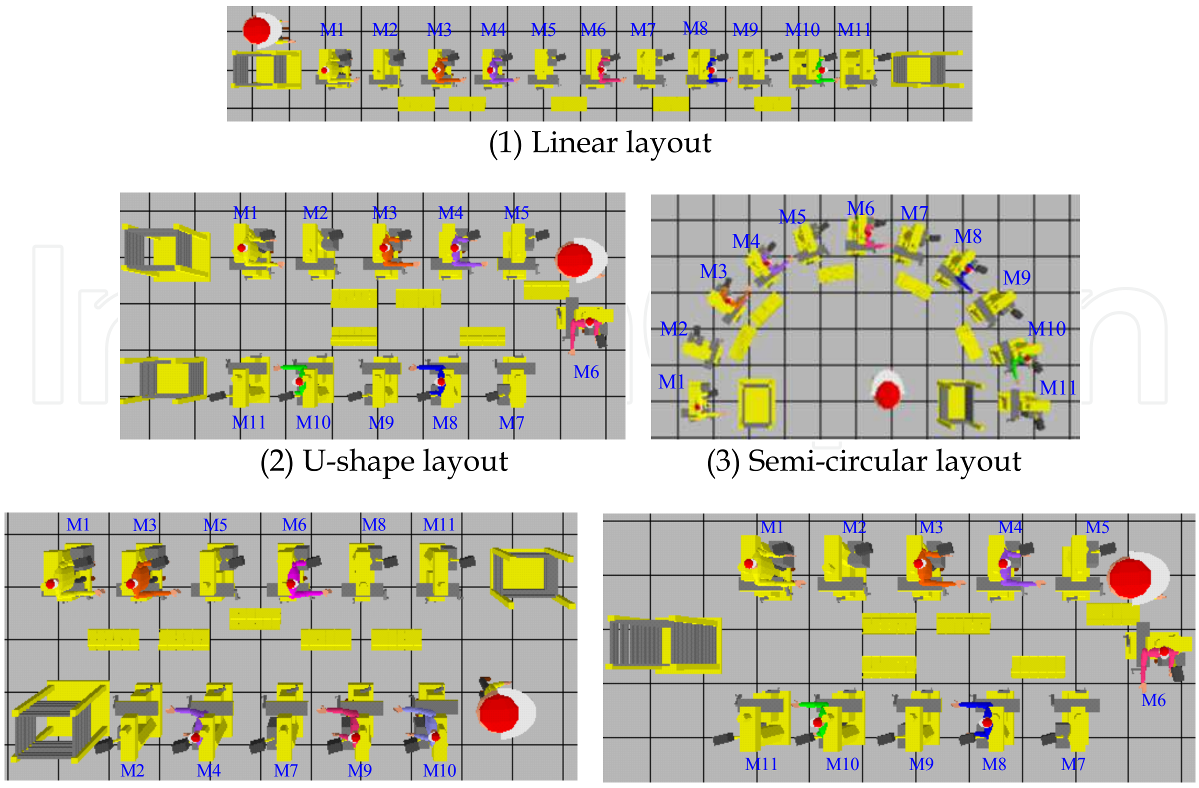

Fig. 11. Simulation model of three types of facility layout

No	Machine	Quantity	Labor	Man-hour(s)	No	Machine	Quantity	Labor	Man-hour(s)
1	M1	1	L1	43.28 (dual-workstation)	6	M6	1	L4	31.3
2	M2	1	L1	74.3	7	M7	1	L4	50.26
3	M3	1	L2	74.3	8.9	M8,9	2	L5	136.2
4	M4	1	L3	36	10	M10	1	L6	70.77
5	M5	1	L3	36	11	M11	1	L6	14.7

Table 10. Man-hour arrangement of piston production line

Type of facility layout	Linear layout	U-shape layout	Semi-circular layout	Multi-line layout	Loop layout
Material handling cost	688.607	723.2155	681.5551	880.5325	662.1082

Table 11. Material handling cost of piston production line (/yuan)

Type of facility layout	Linear layout	U-shape layout	Semi-circular layout	Multi-line layout	Loop layout
Material handling cost	30	48.26	19.096	48.26	66.47

Table 12. Area utilization rate of piston production line (%)

Type of facility layout	Linear layout	U-shape layout	Semi-circular layout	Multi-line layout	Loop layout
Equipment utilization rate	47.19764	51.43864	47.22245	46.719	45.50791

Table 13. Equipment utilization rate of piston production line (%)

Type of facility layout	Linear layout	U-shape layout	Semi-circular layout	Multi-line layout	Loop layout
Labor utilization rate	24.30267	32.38983	25.89	29.1795	27.006

Table 14. Labor utilization rate of piston production line (%)

7.4 Conclusions

In this example, single-row layout, multi-row layout and loop layout are compared with each other first. The backtracking and bypassing in linear layout are introduced. Due to customers' demand for as possible as low selling price of a product, the concept of manufacturing cost is presented secondly. Based on analyzing the components of manufacturing cost, four models are established lately. These models describe the function of material handling cost, area utilization rate, equipment utilization, and labor utilization, respectively. Through modeling and simulation on QUEST platform, three types of facility layout (linear, U-shape, semi-circular, multi-line, and loop) are compared finally. From above discussion, some conclusions can be achieved as follows: (1) material handling cost of loop layout is lowest among the three types of facility layout; (2) area utilization rate of loop layout is higher than the others; (3) equipment utilization of U-shape layout is the higher than others in the same moment; (4) labor utilization of U-shape layout is highest, and linear layout is the worst.

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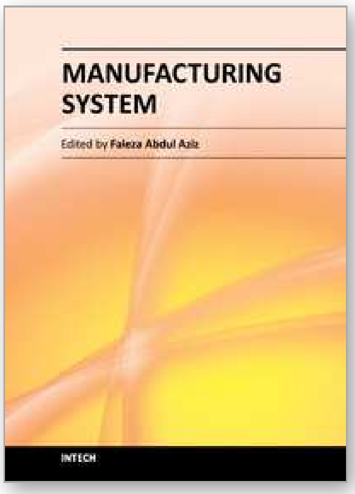

Manufacturing System
Edited by Dr. Faieza Abdul Aziz

ISBN 978-953-51-0530-5
Hard cover, 448 pages
Publisher InTech
Published online 16, May, 2012
Published in print edition May, 2012

This book attempts to bring together selected recent advances, tools, application and new ideas in manufacturing systems. Manufacturing system comprise of equipment, products, people, information, control and support functions for the competitive development to satisfy market needs. It provides a comprehensive collection of papers on the latest fundamental and applied industrial research. The book will be of great interest to those involved in manufacturing engineering, systems and management and those involved in manufacturing research.

How to reference
In order to correctly reference this scholarly work, feel free to copy and paste the following:

Xiaohong Suo (2012). Facility Layout, Manufacturing System, Dr. Faieza Abdul Aziz (Ed.), ISBN: 978-953-51-0530-5, InTech, Available from: http://www.intechopen.com/books/manufacturing-system/facility-layout

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中国上海市延安西路65号上海国际贵都大饭店办公楼405单元
Phone: +86-21-62489820
Fax: +86-21-62489821