Rating and Adjacency Problems in Facility Layout Construction

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The facility layout problem attempts to minimize material handling costs, maximize specialization, or optimize a two-component function weighing both objectives. The most often used design approach assigns facilities to locations on a discrete divided grid. Considering the single floor problem, this study presents a two-stage heuristic approach. First is the rating stage, using a maximization function, assisted by a rating system, proposed to integrate objective and subjective relationships into one component. Second is the construction stage using a procedure, based on a special Transportation Model, proposed to solve the facility adjacency problem and heuristically locates the facilities with tentative trade-offs. Also, another procedure based on Linear Assignment Model is presented for solving the adjacency problem through superimposing sub-layouts. The latter procedure slightly modifies the formulation proposed for the first. The salient advantage of the proposed approach appears in overcoming the limitations on the number of facilities and objective of subjective relationships which may affect the practitioners in different areas. Moreover, it can be led into as an integral part of other approaches to minimize the effort consumed in constructing large layouts with multiple relationships.

1. Introduction

Generally, for a large manufacturing or service plant, the facility layout problem is the determination of most effective arrangement of the physical facilities therein under specific working conditions. It could be formulated for departments, cells, or machines. The main objective of the problem is to minimize the cost of material handling system in the presence of constraints resulting due to several objective and subjective facors. Bazara and Goode (1975) summarizes different definitions of the layout problem. The problem becomes more complicated with irregular shape facilities, because it adds the task of minimizing the dead space. The problem has been modelled and solved through mathematical and heuristic approaches which can be classified into three categories, construction, improvement, and hybrid construction/improvement (Kusiak and Heragu 1987, Yaman et al. 1993, Welferga and Gibson 1993). Due to the variety of interacting factors, the problem maintains a complex nature and the solution constitutes a difficult task in spite proposing many approaches. Therefore the problem is not settled eventually and most of the proposed approaches don't attract practitioners especially when they have a large number of facilities.

The problem has been modelled in different mathematical approaches such as quadratic assignment (Lawler 1965, Kusiak and Heragu 1987), quadratic set-covering (Bazara and Goode 1975), and graph theory (Freud and Robinson 1978, Al-Hakim 1991, Hassan and Hogg 1987). Earlier, most often used model is the Quadratic Assignment Problem (QAP), which assigns a number of facilities to available locations on a divided rectangular grid such that a cost function is minimized (Al-Rahim et al. 1993, Welferga and Gibson 1993, Askin and Stanbridge 1993). Several solution procedures for such QAP are detailed in Bazara and Goode (1975), El-Rayah and Holler (1978), and Kusiak and Heragu (1987). As a result of input, irregular shapes for facilities weaken the solution of QAP on a discrete grid. As an attempt to deal
with such point of weakness. Heraga (1990) and Heraga and Kusiak (1990) developed a continual plane model.

However, the exact optimum approaches are based on branch and bound or cutting plane techniques and limited to small problems (Welgama and Gibson 1985). Hence, it is found impractical to search the problem solution optimally. Therefore, heuristics were developed to overcome these limitations. The most earlier and popular heuristics were developed in prominent packages such as CORELAP by Lee and Moore 1957, ALDEP by Seboe and Mandelheim 1961, CRAFT by Buflle et al. 1964, and PLANET by Apple and Deisenroth 1972; see Riggs (1976), Hiles (1984) and Yaman et al. (1992). The first two packages are constructive while the latter are improving. Hence, many computer-aided approaches appeared (Lewis and Block 1982, Khator and Moodie 1984).

Construction approaches can be further categorized as graph theory based approaches and conventional approaches (Welgama and Gibson 1975). Also, many heuristics are based on graph theory. Potts and Robins (1976) presented a graph theory-based heuristic and Al-Hakim (1991) applied the graph theory to his two improvement heuristics. Although this theory is conducted to heuristics, it maintains many disadvantages which were discussed in Hastan and Hogg (1991).

Recently, Kaku et al. (1991) developed a hybrid construction/improvement heuristic approach called KTM. Yaman et al. (1993) described a sorting construction heuristic divided into three modules and directed towards minimizing the traveling distances between facilities. Welgama and Gibson (1993) presented a construction algorithm generating machine layout on a continuum, minimizing the material flow cost. This specific algorithm considers some practical aspects and can be extended to general facility layout problem.

More recently, Meller and Gau (1996) presented a sample of recently published layout algorithms by authors and objective functions from 1988 to 1994 and highlighted different review papers including their recent review paper. Moreover, they discussed and examined the three traditional layout objective functions with respect to material handling costs providing a physical interpretation of the weights in the weighted-center facility layout two-component objective function. Also, they developed an objective function based on a basic material handling cost structure. Meller and Gau (1996) considered both single floor and multi floor problems in an improvement type algorithm based on simulated annealing; the relationship between combinatorial optimization techniques and practical problems. In other words, this approach considers an expanded set of facility exchange.

However, the literature proved that there is no efficient algorithm solves the problem optimally and the experimental refinement is a must and most of the current algorithms do not attract the practitioners. The combinations result from the variety of factors that interact in the layout problem. The purpose of this paper is to provide a comprehensive approach which comprises two stages. First, it analyzes the facility relationships through a criterion; combines the existing relationships in a single numerical component and then solves the adjacency problem in constructing a layout. The problem formulation is mainly based on the transportation and linear assignment models.

2. Factors of the Layout Problem

The plant layout problem is subjected to a large variety of factors which are dependent upon the prospective layout, nature of the planned process, material handling system, and other system constraints (such as limited type and number of machinery). The material handling costs is the most common factor, since it explains about 20% to 50% of the total operating costs (Meller and Gau 1992). Such factors are scattered in the literature (Yaman et al. 1993, Akin and Standridge 1993); but, here, they will be comprehensively organized. Generally, the main factors are

1. Number of products,
2. Number of units of each product,
3. Number of facilities (departments, workstations, or machines) of the plant,
4. Sequence of processes of each product (forward and backward movements),
5. Facility sizes,
6. Facility shapes (regular/irregular and dimension limitations),
7. Space availability,
8. Special closeness relationships between facilities. For example two or more facilities should be adjacent because they share fixed or movable facilities or due to other requirements. The system $A, E, f, C, X$ is often used to rate the importance of such closeness (Riggs 1976). These rates can be carefully assigned some arbitrary numeric values. (Yaman et al. 1993, Akin and Standridge 1993).
There are more specific factors that may make the problem more complicated. Some of them depend on the plant location and nature of resources and transportation from/to the plant while others depend on the prospective material handling system, plant construction, and the service utilities. This category comprises:

1. External transportation systems, such as railroads, routes, and resource access. This may restrict the location of shipping, receiving, and other facilities.
2. Urban shapes and locations (they may be specified in advance). They are preferred to be straight as possible in regular rectangles with easy intersections.
4. Services, which are often considered fixed facilities, such as heating-cooling, ventilation, air conditioning, illumination, recycling, networks, water resources, and power resources. These services may restrict the location of one or more facilities according to their requirements.
5. Costs such as material handling costs, which depend on the distance and number of trips between facilities. (backwards motion may weigh over forward motion) and other costs.

The planner may embed other factors to the plant and facility layout problem. Intuitively, the cited factors comprise subjective and objective factors and some of them may be related to each other. For example, the special cost relationships may result from the location of services and/or nature of the available material handling system. The facility relationships are often exhibited using a tabular form.

3. Proposed Methodology

The methodology comprises a numerical function for rating facility relationships and two different procedures for solving the adjacency problem. The first procedure is based on the transportation model and the second is based on the linear assignment model.

3.1 Numerical Rating Function

Both objective and subjective relationships between facilities will be numerically rated and combined into a single function. It is assumed that a plant consists of n facilities such that facilities i and j are joint through an objective relationship, Oij, and mutualize a subjective relationship, Sij. An extension for the number of relationships will be discussed later.

(a) Rating Objective Relationships

The objective may be minimizing the material handling cost; in other words, facilities neighbor as possible. These related by maximum handling requirements such as number of trips per time or number of handling facilities. Suppose that the number of trips is found effective, it can be rated simply in three ways:

- **Base number rating** - A number of trips is rated as a base for all entries. For example, every ten trips are rated one and so on.
- **Adaptive rating** - All entries are related to the maximum entry.
- **Density rating** - Imagine Oij, number of trips, to be a random variable with density function f(a) which may follow a distribution such as linear or exponential. Let a constant and assume an exponential distribution, as shown in Fig. 1.

\[ f(a) = \begin{cases} \beta e^{-\beta a} & 0 \leq a \leq a_{max} \\ 0 & \text{otherwise} \end{cases} \]  

Then, rating of number of trips between facilities can be approximated by the cumulative area under f(a), encompassed by b and c, formally

\[ R(Oij) = \int_b^c f(a) da = \beta e^{\beta b} - 1 \]  

which indicates that the maximum rating will be 100%. It is found more systematic way consolidating for the incremental effect of number of inter-facilities trips per unit time. Of course, the planner may resort to a combination between the three ways.

(b) Rating Subjective Relationships

The objective may be touching the facilities according to their mutual special closeness. This paper presents a term named importance horizontal, if, for the closeness relationship, it is a random variable with
density function \( f(h) \) which may follow a distribution such as linear or exponential. This horizon is divided into a number of equal distances according to the number of importance levels. Suppose that we are concerned with the traditional six levels \( A, E, I, O, U, \) and \( X \), which decay in that order. The level \( X \) is assigned a very large negative value while the others are assigned contiguous areas under \( f(h) \), which is assumed exponential, as shown in Fig. 1.

![Diagram showing importance levels and number of trips](image)

**Fig. 1** Rating special closeness and number of trips using exponential distributions

Assume that \( a \) is constant, \( h_{\text{min}} \) and \( h_{\text{max}} \) are the limits of the horizon, and \( h_1 \) and \( h_2 \) are the limits of an importance, then

\[
f(h) = \begin{cases} \frac{a}{h} & h_{\text{min}} \leq h \leq h_{\text{max}} \\ 0 & \text{otherwise} \end{cases}
\]

Hence, numerical rating of importance of mutual closeness is approximated by the area encompassed by \( h_1 \) and \( h_2 \), formally

\[
R(S_{ij}) = \int_{h_1}^{h_2} f(h) dh = a(e^{-h_1} - e^{-h_2})
\]

The parameters of both equations, in addition to the distribution type, are completely heuristic determinants, but they represent a basic relation to the problem of rating the closeness importance. Here, values of \( h_{\text{min}}, h_{\text{max}}, \) and slope are recommended \( "0", "3", \) and \( "1" \) respectively. The time and experience, of course, will find out different alternatives. Other subjective relationships can be rated in a similar way.

The efficiency of this rating system may diminish when integrated into the system defined for the objective relationships. Suppose that a relationship such as exists due to sharing an expensive equipment, then fitness should be penalized relative to the cost of duplicating equipment. This penalty can be estimated in different ways such as multiples of interfacility material handling cost (or number of trips) which replaces such subjective relationship. By this way, most of the subjective relationships can be replaced. A fixed facility on the plan can be included as a zero area facility. It is obvious that a relationship such as \( X \) always separates by its large negative value.

(c) Final Weighted Rating

Suppose that the current objective relationship simulates the number of trips per time and the current subjective relationship simulates the special closeness. Hence, the total rating between facilities \( i \) and \( j \) is

\[
R_{ij} = \lambda_j R(O_{ij}) + (1 - \lambda_i) R(S_{ij})
\]

where \( \lambda_i \) is the weight awarded to the objective relationship between facilities \( i \) and \( j \). Such weight may be constant for all facilities. It may be regulated, if both are equally weighted. A useful concept, the central facility, is mentioned. It may be defined in many ways (Askari and Standridge 1992), whilst here it will be defined as the facility which registers maximum global rating, \( \text{GR}_i \), where

\[
\text{GR}_i = \sum_{j=1}^{n} R_{ij}
\]

This facility, actually, has significant relationships with one or more of other facilities. For due concern, we should ignore the \( X \) relationship, because of very negative value would lead to fallacious global ratings. Also, the rating mean and standard deviation are two important indicators for the benefit of central facility.
Therefore, little coefficient of variation (CV) should not be neglected. However, for nearly uniform facility shapes and uniform available space, the digit of \( n_g \) is proposed as a guide for the maximum number of central facilities since in such a case when having at least five facilities, a central facility could be attached in four sides.

### 3.2 Assumptions

A planner may impose several assumptions for simplification or other purposes. The most significant assumptions include:

1. The problem is formulated with a static deterministic environment.
2. Material handling cost between facilities is a direct function of the number of trips per time and traveled distance.
3. Distance between facilities is an output parameter if another alternative is used as an input, such as number of trips per time.
4. Facilities are square or rectangular in shape.
5. The flow pattern may be imposed in advance such as spine-oriented straight line.

A fixed facility relationship between two or more facilities should be coded significantly. In other words, if a facility is restricted by another facility, they should be manipulated as one area. These codes' choice depends on the user, they may be numbers and/or letters displaying positions such as Right/Left or Up/Down.

### 3.3 Problem Formulation and Solution

Most of the facility layout approaches attempt to minimize material handling cost (distance-based), maximize special closeness (subjective adjacency-based), or minimizing weighted two-component objective function: see Moller and Gau (1996) for details. The salient disadvantage of the third objective function appears when an additional factor interacts which, in turn, complicates the task of relating a relative weighting factor. Here, the objective will be to construct a layout which maximizes special closeness and minimizes material handling costs. This is implicitly equivalent to minimizing the traveling distances between the facilities according to their total mutual rating. The derived numerical scaling function combines both objectives into a single-component maximization function. Here, it is proposed to formulate the problem as

\[
\text{Maximize} \quad \sum_{i} \sum_{j} x_{ij} R_{ij}
\]

Subject to

\[
\sum_{j} x_{ij} \leq \theta_i \quad \text{for } i \text{'s as sources}
\]

\[
\sum_{i} x_{ij} = 1 \quad \text{for } j \text{'s as destinations}
\]

\[
x_{ij} \in \{0, 1\}
\]

This linear programming model can be reformulated as a special transportation model (maintains an assignment property) as proposed in Table 4. Thus making it easy to provide a near-optimal solution. The decision variable \( x_{ij} \) is set to 1 if facilities \( i \) and \( j \) should be adjacent, otherwise it is set to 0. The parameter \( \theta_i \) (a digit \( \geq 0 \); variable constant) is proposed, guided by G.R., to express the number of facilities that could be adjacent to facility \( i \) especially when \( i \) is central; this also depends on the facility space requirements. This problem assigns facilities to facilities, therefore, it is not a lower bound on QAP which assigns facilities to locations (Askin and Standridge 1992, Yaman et al. 1993, Welgma and Gibson 1993).

The regular transportation model (balanced minimization form) solves the adjacency problem. Hence, a rectangular draw (divided grid) is suitable for realizing the attachment between facilities as shown in Fig. 2.

Here, the question would be Right/Left or Up/Down? Which also may be restricted by fixed facilities. The facilities which are restricted by fixed facilities are located directly with minor switches. The heating process is treated with some trade-offs maintaining adjacent facilities with maximum rates.
The final rectangular realization is converted to a space diagram showing facility space and shape requirements, aisles, and special fixed facilities. If the flow pattern and facility shapes are specified as input, the space relationship becomes more deterministic but it may add difficulty. The refinement may need to facility switching which must be made in a manner keeping the shape integrity and adjacency of facilities. The planner may be forced to pass an aisle between adjacent facilities, such decision should be made carefully to maintain a compatible degree of adjacency.

The main principle of the alternate procedure is to solve a sequence of linear assignment problems which can be dealt with using Hungarian algorithm. Hence, the right side of inequality 8 is modified to = 1 which removes the slack column and last column in Table 4. The original problem solution results in paired combinations (sub-layouts) of facilities such that the total rating is maximized, adjacency is maximized. Thereafter, a new smaller problem is solved for those combinations, and so on until reaching the final problem. Notice that after the problem reaches two or three combinations it can be settled using the original rates of the peripheral facilities. A three combinations problem can be directly solved using the principal of central combination.

The mutual rates between each two combinations are estimated using eq. (12) next, therefore provisions should be taken for the undesirable relationships and exhibited on the assignment table. Assigned facilities or combinations are crossed row wise and column wise that may lead to unassigned items in an iteration as shown in Table 5 (combination 1 is the same as 3). 

Intuitively, the ratio between two combinations is a direct function of the mutual rates between the facilities in both sides. For two-facility combinations, #1 (A and B facilities) and #2 (C and D facilities), the equivalent mutual ratio is theoretically proposed as

$$R_{12} = \max(\max(R_{AC}, R_{AB}), \max(R_{BD}, R_{AD})) = \max(\max(R_{AC}, R_{BD}), \max(R_{AD}, R_{AB}))$$  \hspace{1cm} (11)

or generally for multi-facility combinations

$$R_{12} = \max\left(\sum_{i=1}^{m} \max\{R_i\}, \sum_{j=1}^{n} \max\{R_j\}\right)$$  \hspace{1cm} (12)

At each iteration, this procedure locates the facilities in each combination under the resultant adjacency. It attaches each two combinations in a manner maximizing the rates between the facilities in both sides. Therefore, attachments may force the planner to make some iterative switching with insignificant effect on the total rating in the final layout. The principal of central facility is used within each combination plot to reduce the expected number of switches. Also, the final results can be visualized using a divided grid and a space diagram showing the shape details. Also, this procedure is not a lower bound on QAP because it assigns facilities to facilities not facilities to locations.

3.4 Extension of Relationships

Suppose that a plant consists of $n$ facilities such that facilities $i$ and $j$ joint through $l$ objective relationships, $(O_1), (O_2), \ldots, (O_l)$, and mutually $m$ subjective relationships, $(S_1), (S_2), \ldots, (S_m)$. First, it is assumed that those relationships are rated and directed to the same objective. Hence, the total rating between facilities $i$ and $j$ is modified to

$$R_{ij} = w_1 \sum_{O \in O} w_1 R(O)_{ij} + (1 - w_1) \sum_{S \in S} w_1 R(S)_{ij}$$  \hspace{1cm} (13)

where $w_1$ is the weight awarded to the objective relationship between facilities $i$ and $j$, $w_2$ weights $O$, and $w_3$ weights $S$. However, ratings may be approximated in many ways, validating an algebraic sum, as followed in section 3.1. Both types of relationships should be rated and summed in a maximization direction.

4. Illustrative Manipulation

Suppose that we are encountered with the problem of constructing the layout which has the data shown in Table 1. Each tabular cell contains a letter expressing the special closeness importance and a number expressing the number of trips per hour between the departments. The $d, E, C, O, U, X$ system is assumed for the special closeness.
### Table 1: Initial from-to special closeness and number of trips per hour

<table>
<thead>
<tr>
<th>Dept</th>
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</table>

The letter explains the importance of closeness relationship and the number explains the number of trips per hour.

The rating process is completed using the system proposed in section (2.1) as shown in Tables 2 and 3.

### Table 2: Rating the number of trips

<table>
<thead>
<tr>
<th>No. of trips</th>
<th>0%</th>
<th>10%</th>
<th>20%</th>
<th>30%</th>
<th>40%</th>
<th>50%</th>
<th>60%</th>
<th>70%</th>
<th>80%</th>
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<th>100%</th>
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<td>Usage (%)</td>
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<td>70%</td>
<td>80%</td>
<td>90%</td>
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*Each trip is assumed 0.3 point for Op = 1 and 0 otherwise.*

### Table 3: Rating the special closeness

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<th>Level</th>
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<th>B</th>
<th>C</th>
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<tr>
<td>Rate (%)</td>
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<td>30</td>
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**H = 0.5; h = 3; Step 1: w = 0.066; M is large

### Table 4: Numerical rating (final %) from-to and statistical calculations

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The slack column in transportation tables should be assigned zero after switching is the maximization equivalent. Any suitable transportation technique can be used to solve the regular problem.

### Table 4 Indications

Table 4 indicates that department 6 suits the central position of the plane because it registers maximum total rating with minimum CV. Therefore, if any 5 can be assigned 4 (the sides of departments don't allow more) while other 6 or 7 could be assigned 4 or less (e.g., 2). The solution of the regular transportation problem is shown by bold cells on Table 4. Fig. 2-4 shows a rectangular realization for the departmental adjacency which can be easily converted to a space diagram showing the aisles and space requirements. It is obvious that department 6 is optimally positioned between departments 3, 5, 8, and 9, therefore department 8 could be switched as shown in Fig. 2-6 with compatible total rating.
However, the geometry of the available space and departments is an important determinant for the proposed switches. For instance, if the departmental geometry is completely uniform, it may be possible to switch department 4 as shown in Fig. 2-c to minimize the dead space.

Table 5 summarizes the results of the alternate procedure showing departmental assignments. The problem ends with three combinations X, Y, and Z which are superimposed using the rates of the peripheral departments.

The expected switching of department 3, in Fig. 3, is advantageous only when the space is limited. Also, departments 3 and 5 can be successfully exchanged. The resultant layout is different from that results from the first procedure with maintaining near equal rates. However, the difference between both procedures is dependent upon the value of "δ" proposed for the first procedure.

5. Conclusions

The results proved that the layout construction and improvement are combinatorial problems especially when the number of facilities and shape requirements increase. Therefore it is difficult to solve the problem optimally without using integer refinement, where the approach used. A non-iterative and iterative constructions procedures are presented for solving the adjacency problem with a manner reaching the best solution with minor switching as proved by the case manipulated. Also, presented rating mechanism reduces the problem parameters and addresses economical considerations of qualitative relationships by imposing the penalty principal. The problem is formulated in a different fashion which combines all problem objectives in a single function avoiding the objective weighting. Thus making it possible to accommodate a large variety of facility relationships and a large number of facilities.

Although the current procedures are based on the transportation and assignment models, they are considered simple mathematically based heuristics. Both procedures are not lower bounds on QAP which resorts to complicated computations. Therefore both are advised for practitioners using microcomputers. Further, practitioners may focus on reducing the dual space in the final layout which exhibits other considerations such as aisles and existing facilities or buildings. Such considerations can be manipulated by considering them on the model of basic facilities using specific codes. If aisles is not specified in advance, the resultant layout may be subjected to some facility switching. Moreover, the approach can be partially or completely utilized in other construction approaches to provide a starting solution for an improvement approach.

However, the facility layout problem could not be settled eventually and still needs an extensive research work. From analysis view, it is recommended to resort to mathematically based heuristics. From practical view, it is recommended to empower the matter to team work having practical and industrial experience.
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References


