Designing Departure Facility Layout at Airport Passenger Terminals

JIN-RU YEN*, HSIU-FEN LIN, and CHIN-WU CHU
Department of Shipping and Transportation Management
National Taiwan Ocean University
No. 2, Peining Rd. Keelung 202
TAIWAN, ROC
jryen@ntou.edu.tw (www.ntou.edu.tw)*

Abstract: The research applies the idea of facility layout to solve the problem of airport passenger terminal design. Specifically, a mathematical programming formulation is developed to solve the defined problem by minimizing the flow-distance of total passengers. Among the proposed eight design alternatives for departure passengers, the optimum solution is obtained by applying the formulation. The empirical results validate our framework and formulation that can be applied to other airport design problems.

Key-Words: - Airport landside, facility layout, mathematical programming.

1 Introduction
An airport system can be divided into three components based on different activities: airside, passenger terminals, and access facilities. Airside is directly related to aircraft operations, including aprons, taxiways, runways, air traffic control systems, and other navigation facilities. Passenger terminals contain the area at which passengers enter/leave the airport, enplane and deplane, and incur necessary processes for departure/arrival such as check-in, security check, and baggage-claim. Access facilities consist of airport access roads, parking lots, or other modes of public transportation. Among those three components, the passenger terminal is considered as the most complicated one in that no standard design criteria are available in the airport industry or academic arena. To address this problem, this study aimed at proposing a framework to apply the idea of facility layout to the design of passenger terminals at the airport.

The facilities layout problem (FLP) is the problem of determining the physical layout of a service or manufacturing system, i.e. the arrangement of facilities within a given space, in a way to increase effective and economical use of space (Suresh and Shu, 1993). The FLP can be considered as one of optimization problem, which focuses on the organization of a company’s physical facilities to minimize the cost of interaction between facilities subject to certain constraints. Because facilities usually have unequal sized and facility sites are not pre-specified in real-world problems, a number of mathematical model have been developed for unequal-area FLP. These include a mixed integer programming (MIP) model by Montreuil (1990) and a nonlinear mathematical programming model by van Camp et al. (1991). Moreover, there have been efforts to solve unequal-area FLP using a computer-based heuristic algorithm (Armour and Buffa, 1963; Tam, 1992; Tate and Smith, 1995; Hon-iden, 1996).

Muther’s systematic layout planning (SLP) (Muther, 1973) is the infrastructure to solve a facility layout design problem that mainly uses the quantitative and experience analysis method. The SLP is suitable for all kinds of industries to provide layout design guidelines in practice (Fang and Wang, 2004). The SLP procedure of the facility layout design is mainly involved in the following steps: input data and activities, relationship diagram, space relationship diagram, develop layout alternatives, and evaluation.

2 Method
2.1 Problem setting and description
The objective of this research is to apply the idea of facility layout to solve the problem of passenger terminal design. The processes that a international departure/arrival passenger are required to participate in include check-in, security check, passport/visa check, waiting for departure, baggage claim, and customs check. Additionally, there are some commercial activities that are optional to the passenger, such as resturants, duty free shops, and other utility services. By applying the idea of facility layout and consulting experts in airport design area, we define eight layout alternatives for terminal II of the Taiwan Taoyuan (CKS) international airport. Each alternative is solved by the mathematical programming formulation developed in the following section, with the objection function that minimize the flow-distance.
2.2 Mathematical formulation and layout design

To precede the analysis, we formulate our mathematical model based on the following assumptions.

1. The shape of the planning terminal is rectangular and the width, length and area of the planning terminal are known.
2. Each area of the planning terminal is clearly defined. The shape of each area is rectangular and the space requirement of each area is given.
3. The planning terminal is a single-story building.
4. The distance between areas is based on the rectilinear distance (so called rectangular, metropolitan or Manhattan distance). If the centroid coordinates for area A and area B are \((X_a,Y_a)\) and \((X_b,Y_b)\), respectively, we define the rectilinear distance between area A and area B as \(|X_a - X_b| + |Y_a - Y_b|\).
5. In this design, aisles not only should be placed between the lobby and commercial area A, but also should be placed between the arrival immigration hall and departure lounge area.
6. Only departure passengers are considered without taking transfer passengers into consideration.

In the following we present the integer programming model and relevant notations:

\[
\begin{align*}
\text{Min} Z &= \sum_{i=1}^{n} \sum_{j=1}^{m} F_{ij} D_{ij} = \sum_{i=1}^{n} \sum_{j=1}^{m} F_{ij} (|L_i - L_j| + |W_i - W_j|) \\
&= \sum_{i=1}^{n} \sum_{j=1}^{m} F_{ij} (L_i - L_j - R_i + S_j + W_i - W_j - R_j + S_j) \\
&\text{s.t.} \quad \sum_{i=1}^{n} L_i \times W_i + \sum_{k=1}^{m} CL_k \times CW_k \\
&\quad \leq TA_p \quad \text{for area } B \quad \text{given } CL_k \text{ and } CW_k \leq TA_q \\
&\quad A_{ip} \leq L_i \times W_i \quad i = 1, \ldots, n \\
&\quad L_i \times W_i \leq A_{iq} \quad i = 1, \ldots, n \\
&\quad L_i \leq \sum_{i=1}^{n} L_i \quad \forall i \in Nh \\
&\quad L_i \leq L_q \quad i = 1, \ldots, n \\
&\quad W_i \leq \sum_{i=1}^{n} W_i \quad i = 1, \ldots, n \\
&\quad \sum_{i=1}^{n} W_i \leq W_q \quad i = 1, \ldots, n \\
&\quad CW_k \geq K \quad k = 1, \ldots, m \\
&\quad W_i - W_j - R_j + S_j = 0 \\
&\quad L_i - L_j - R_j + S_j = 0 \\
&\quad L_i \geq 0; \quad W_i \geq 0; \quad R_j \geq 0; \quad S_j \geq 0; \quad CW_k \geq 0; \quad CL_k \geq 0; \quad i = 1, \ldots, n; \quad j = 1, \ldots, n; \quad k = 1, \ldots, m
\end{align*}
\]

\(Z\): total flow distance. 
\(n\): the number of planning areas. 
\(m\): the number of aisles. 
\(i\): \(\{i = 1, \ldots, n\}\) the index set of planning areas. 
\(j\): \(\{j = 1, \ldots, n\}\) the index set of planning areas. 
\(k\): \(\{j = 1, \ldots, m\}\) the index set of aisles. 
\(Nh\): the set of areas placed in the \(h\)th row of the layout design. 
\(Mv\): the set of areas placed in the \(v\)th column of the layout design. 
\(F_{ij}\): the passenger flow between area \(i\) and area \(j\). 
\(D_{ij}\): the distance between area \(i\) and area \(j\). 
\(TA_p\): the total space requirement of the planning terminal at service level \(p\). 
\(TA_q\): the total space requirement of the planning terminal at service level \(q\). 
\(A_{ip}\): the space requirement of area \(i\) at service level \(p\). 
\(A_{iq}\): the space requirement of area \(i\) at service level \(q\). 
\(L_i\): the length of area \(i\). 
\(W_i\): the width of area \(i\). 
\(R_j\), \(S_j\) new decision variables denoting the vertical distance or the horizontal distance between areas. By defining two new variables \(R_j\) and \(S_j\), such that 
\[
R_j = \begin{cases} 
L_i - L_j, & L_i \geq L_j \\
0, & L_i < L_j 
\end{cases} 
\]
and 
\[
S_j = \begin{cases} 
0, & W_i \geq W_j \\
W_j - W_i, & W_i < W_j 
\end{cases} 
\]
or 
\[
R_j = \begin{cases} 
W_i - W_j, & W_i \geq W_j \\
0, & W_i < W_j 
\end{cases} 
\]
The objective is to minimize total flow-distance between areas and find the optimal length and width of these areas. The first term, \( \sum_{i=1}^{n} \sum_{j=1}^{n} F_{ij} D_{ij} \), of objective (1) is summing up flow-distance (the product of flow volumes between areas and the distances between areas) between areas. As mentioned above, the distance between areas is based on the rectilinear distance. The first term is identical to the second term, \( \sum_{i=1}^{n} \sum_{j=1}^{n} F_{ij} \left( L_{i} - L_{j} \right) + \left| W_{i} - W_{j} \right| \), of objective (1).

By defining two new decision variables \( R_{j} \) and \( S_{j} \), the second term can be represented as a linear programming problem, \( \sum_{i=1}^{n} \sum_{j=1}^{n} F_{ij} \left( L_{i} - L_{j} - R_{j} + S_{j} + W_{i} - W_{j} - R_{j} + S_{j} \right) \).

Constraints (2) and (3) ensure that summing up the area of each planning area and each aisle will satisfy the total space requirement of the planning terminal at service level \( p \) and \( q \), respectively. Constraints (4) and (5) are the space requirement constraints for every planning area. Constraints (6) and (7) ensure that the length of the layout design at two different service levels, \( p \) and \( q \), will be in the range \( \left[ L_{p}, L_{q} \right] \). Constraints (8) and (9) ensure that the width of the layout design at two different service levels, \( p \) and \( q \), will be in the range \( \left[ W_{p}, W_{q} \right] \). Constraint (10) is the minimum width of aisle constraint. The minimum width of aisle can be calculated based on the traveling speed and the flow volumes of passengers. Constraints (11) and (12) are transformation constraints which are used to transform \( \sum_{i=1}^{n} \sum_{j=1}^{n} F_{ij} \left( L_{i} - L_{j} + \left| W_{i} - W_{j} \right| \right) \) of objective (1) into a linear programming problem, \( \sum_{i=1}^{n} \sum_{j=1}^{n} F_{ij} \left( L_{i} - L_{j} - R_{j} + S_{j} + W_{i} - W_{j} - R_{j} + S_{j} \right) \).

As mentioned in the fourth assumption, the distance between areas is based on the rectilinear distance. If the centroid coordinates for area \( i \) and area \( j \) are \((X_{i}, Y_{i})\) and \((X_{j}, Y_{j})\) respectively, we define the rectilinear distance between area \( i \) and area \( j \) as \( \left| X_{i} - X_{j} \right| + \left| Y_{i} - Y_{j} \right| \). Because the length and width of every area are decision variables in our model, we cannot know the length and width of every area without solving the model. Since \((X_{i}, Y_{i})\) and \((X_{j}, Y_{j})\) cannot be determined before solving the model, \( \left| X_{i} - X_{j} \right| + \left| Y_{i} - Y_{j} \right| \) must be used to represent horizontal and vertical distances, respectively. Given a specific layout design, \( \left| X_{i} - X_{j} \right| + \left| Y_{i} - Y_{j} \right| \) can be represented equivalently as a linear programming problem by adding two new decision variables \( R_{j} \) and \( S_{j} \) and either constraint (11) or constraint (12). Constraint (11) corresponds to the distance of \( L_{i} - L_{j} + W_{i} - W_{j} \) and constraint (12) corresponds to the distance of \( W_{i} - W_{j} + L_{i} - L_{j} \).

### 3 Empirical Results

This study uses the Taiwan Taoyuan (CKS) international airport terminal II as a case study to demonstrate the applicability of the developed mathematical model. Through the procedure of systematic layout planning, including analyzing passengers’ process and the relationship between areas, calculating passenger flows between areas, and measuring space requirement of departure area, the optimal length, width and area of each departure area is done by LINGO algorithm. It determined the facility layout patterns of the minimum flow-distance in the airport departure passenger terminal. We present below the steps used in interpreting the operational procedure to obtain solution for alternatives.

Based on the analysis of passenger process of the terminal II of Taiwan Taoyuan (CKS) international airport, departure passenger route planning can be classified into four types of routing paths. Meanwhile, according to the relationship between areas, eight departure facility layout alternatives could be developed.

Passenger traffic of each departure area could be obtained through questionnaire collection. Departure passenger traffic, during peak hours of the terminal II of Taiwan Taoyuan (CKS) international airport was about 4005 persons/times in 2006. Multiplying this by the percentage of each routing path, as learned from the questionnaire survey, we can obtain the
number of passengers of each routing path of departure passengers during peak hours. Passenger routing regions and commercial space requirement of departure area were based on data provided by the Institute of Transportation, Taiwan, ROC. as input data of airport passenger terminal design and layout. The space requirement of each departure area at service level B and C are shown in Table 1.

Table 1  Space requirement of each departure area at service level B and C

<table>
<thead>
<tr>
<th>Departure area</th>
<th>Service level B (m²)</th>
<th>Service level C (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Check-in counter</td>
<td>2973.2</td>
<td>2401.0</td>
</tr>
<tr>
<td>Commercial space A</td>
<td>1781.3</td>
<td>1415.9</td>
</tr>
<tr>
<td>Security check</td>
<td>1028.8</td>
<td>962.0</td>
</tr>
<tr>
<td>Passport Inspection</td>
<td>1977.1</td>
<td>1022.6</td>
</tr>
<tr>
<td>Commercial space B</td>
<td>16032.0</td>
<td>12743.3</td>
</tr>
<tr>
<td>Departure lounge</td>
<td>39104.0</td>
<td>30784.0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>89654.4</strong></td>
<td><strong>70938.8</strong></td>
</tr>
</tbody>
</table>

Note: Space requirement area at service level B/C is the lower bound value.

Each departure facility layout alternative is substituted into the mathematical model, while each alternative corresponds to a set of objective functions and constraints. The solutions are obtained by using LINGO 10.0. First, we suppose the length and width of the total space requirement of departure area, as based on the length/width ratio of the existing base of the terminal II of Taiwan Taoyuan (CKS) international airport, which is about 3:5. The space requirement of departure area at service level B is 89654.4m², length is 386.5m, and width is 232.0m. The space requirement of departure area at service level C is 70938.8 m², length is 343.9m, and width is 206.3m. Next, according to the total space requirement of departure area at service level B and C, and their respective lengths and widths, the data can be substituted into the mathematical model to obtain the solutions for eight departure facility layout alternatives. The mathematical model can determine the optimal length and width of each area of service level C, under various alternatives, and then the minimization of the total flow-distance is obtained. While eight departure facility layout alternatives were run, the top three alternatives are illustrated in Figures 1-3, respectively. The optimal length, width and area of each departure area are summarized in Table 2.

4 Conclusion
The effectiveness of a layout design cannot be completely measured if the passenger flows and working distances within the airport passenger terminal are ignored. Moreover, departure facility layout methodologies should not only evaluate the quantitative information, but also the formalization of adjacency relations between facilities. This study presented a mathematical model and solution procedure that integrated mathematical programming and SLP procedure in facility layout design. We applied the Taiwan Taoyuan (CKS) international airport departure passenger terminal II as a case study to assume the problem of arranging departure areas on a plant with a single floor. Coupled with passenger process analysis, the service level and space requirement of departure area, the
proposed mathematical model determines the optimal length and width of individual area for eight alternatives, and then the best available passenger route planning can be expressed. Through a series of computational test performed on a set of departure facility layout alternatives, we have showed that alternative 4 is superior to the other alternatives for the minimum total flow-distance. In particular, we found that the objective value (flow-distance minimization objective) has no absolute correlation with total area of departure regions. Departure facility layout alternatives with the smallest objective value may not indicate minimal total area of departure regions (alternative 4: total area = 71309.0, min. total flow-distance = 10756890; alternatives 1: total area = 71173.4, min. total flow-distance = 14100050). Therefore, the results imply that facility layout may affect the design of passenger route planning and influence the minimum flow-distance in the airport departure passenger terminal.

The major practical implications of our research lie in the following aspects:
(1) We formulated a mathematical model that accurately captures the optimal length, width and area of each planning area at certain service levels. That is, if airport designers attempt to plan the airport passenger terminal layout for service level B, they can compute the total space requirement of the planning terminal at service level A and B. Then, the data can be substituted into the mathematical model to obtain the minimum total flow-distance at service level B. This study offers directions for airport designers who can use the proposed methodology to plan airport passenger terminal layouts, thus allowing passengers to have a smooth movement route throughout the terminal building.
(2) We also found that dividing a rectangular base into two lines of airport departure passenger terminal configurations could minimize passenger walking distance. In terms of alternative 4 and alternative 1 which have the minimum total flow-distance, departure check-in counter can be established in one line, putting the other departure area in the other adjacent line; or put departure check-in counter, commercial space, and security check in one line, and put other departure areas in the other line. The analytical results also show that if non-controlled commercial space A and security check are adjacent arranged, it will reduce the distance for departure passengers to travel from commercial space A to security check. Moreover, compared with the departure configurations in Taiwan Taoyuan (CKS) international airport passenger terminal II, they are approximate to dividing the rectangular based into five lines which similar to alternatives 7 developed in this study. To minimize passenger walking distances, we suggested that airport designers should arrange commercial space in a controlled region and departure lounge in one line. After passengers go through passport inspection, they can choose from channel to stop over in commercial space, or go to the departure lounge for boarding.

References
<table>
<thead>
<tr>
<th>Departure area</th>
<th>Length (m)</th>
<th>Width (m)</th>
<th>Local area (m²)</th>
<th>Total area (m²)</th>
<th>Min. total flow-distance (passenger * m)</th>
<th>Length (m)</th>
<th>Width (m)</th>
<th>Local area (m²)</th>
<th>Total area (m²)</th>
<th>Min. total flow-distance (person * m)</th>
<th>Length (m)</th>
<th>Width (m)</th>
<th>Local area (m²)</th>
<th>Total area (m²)</th>
<th>Min. total flow-distance (passenger * m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Departure check-in counter (DC)</td>
<td>343.9</td>
<td>69.9</td>
<td>24038.6</td>
<td></td>
<td></td>
<td>312.5</td>
<td>76.9</td>
<td>24031.3</td>
<td></td>
<td></td>
<td>343.9</td>
<td>69.8</td>
<td>24004.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Commercial space A (CSA)</td>
<td>137.6</td>
<td>10.3</td>
<td>1417.3</td>
<td></td>
<td></td>
<td>75.3</td>
<td>18.9</td>
<td>1423.2</td>
<td></td>
<td></td>
<td>342.3</td>
<td>4.1</td>
<td>1403.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Security check (SC)</td>
<td>137.6</td>
<td>7.0</td>
<td>963.2</td>
<td></td>
<td></td>
<td>76.9</td>
<td>12.6</td>
<td>968.9</td>
<td></td>
<td></td>
<td>343.9</td>
<td>2.8</td>
<td>962.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Passport Inspection (PI)</td>
<td>137.6</td>
<td>7.5</td>
<td>1032.0</td>
<td></td>
<td></td>
<td>130.0</td>
<td>7.9</td>
<td>1027.0</td>
<td></td>
<td></td>
<td>343.9</td>
<td>3.0</td>
<td>1031.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Commercial space B (CSB)</td>
<td>136.0</td>
<td>93.8</td>
<td>12756.8</td>
<td>71390.0</td>
<td></td>
<td>128.4</td>
<td>99.3</td>
<td>12750.1</td>
<td>71173.4</td>
<td>14100050.0</td>
<td>127.2</td>
<td>100.2</td>
<td>12745.4</td>
<td>71140.1</td>
<td>1505900.0</td>
</tr>
<tr>
<td>Departure lounge (DL)</td>
<td>223.8</td>
<td>137.6</td>
<td>30794.9</td>
<td></td>
<td></td>
<td>236.8</td>
<td>130.0</td>
<td>30784.0</td>
<td></td>
<td></td>
<td>242.0</td>
<td>127.2</td>
<td>30782.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Channel 1 (C1)</td>
<td>137.6</td>
<td>1.6</td>
<td>220.2</td>
<td></td>
<td></td>
<td>18.8</td>
<td>1.6</td>
<td>30.1</td>
<td></td>
<td></td>
<td>4.1</td>
<td>1.6</td>
<td>6.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Channel 2 (C2)</td>
<td>93.7</td>
<td>1.6</td>
<td>149.9</td>
<td></td>
<td></td>
<td>99.2</td>
<td>1.6</td>
<td>158.8</td>
<td></td>
<td></td>
<td>127.2</td>
<td>1.6</td>
<td>203.5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>