Location of New Large Aircraft
Gate Positions at Pier Terminals

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Abstract

The advent of the New Large Aircraft (NLA) will impose a series of problems on airports. Most existing airports were not designed to accommodate aircraft larger than the Boeing 747, and new airports will have to be designed so as to cope with NLA. The location of NLA gate positions in the passenger terminal is of importance to landside operations. Two of the most important parameters of terminal design efficiency – passenger walking and baggage transfer distances – will be directly affected by the location of the NLA gates. This paper will provide a discussion on the location of NLA gates in the passenger terminal. Based on the proportions of hub transfer passengers, a mathematical formulation is derived for pier terminals to help in the choice of the specific location of NLA gates that will minimize passenger walking distance. Two basic cases of pier terminals are considered: access to the main building through the pier base; and access to the main building via the middle of the pier.

Introduction

New Large Aircraft (NLA) are defined as new aircraft developments that will be larger than any existing aircraft. In general, the term NLA has been applied to new aircraft larger than the Boeing 747 [Chevallier & Gamper, 1996]. Boeing, McDonnell-Douglas – now merged in one company – and Airbus, all have done studies to build an NLA, but it is Airbus with its all-new A3XX that is taking the lead by announcing the A3XX entry into service in 2005 [Airbus, 1999]. Boeing is now considering building stretched derivatives of the 747, and has announced no plans to build an all-new NLA in the near future.

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Virtually every aspect of airport planning and operations will be influenced by the introduction of the NLA. In a nutshell, the greater physical dimensions of the NLA will affect the design and operation of the airside, whereas its larger passenger capacity will affect the passenger terminal operation and design parameters. An extensive list of the issues related to the compatibility between airports and the NLA can be found in a report produced by the FAA Office of System Capacity [1998] and in Barros & Wirasinghe [1997, 1998a].

Both new and existing airports may find themselves in a situation where a new terminal must be planned to accommodate NLA operations. New airports that intend to efficiently serve the NLA will have to provide at least a small number of compatible gate positions, even if the expected number of NLA operations is relatively small. Should the number of operations be greater, so will the need for NLA gate positions. Existing airports may adapt to NLA operations by either converting existing gates to NLA ones, or building a new terminal or satellite. The former would be preferred should the number of NLA operations be small and if it will not require significant restrictions on airside operations. There are at least three cases, however, in which the construction of a new terminal may be required: (1) where the number of NLA positions necessary to meet the demand is relatively high, making the conversion of existing positions excessively costly; (2) where the existing apron configuration would impose too many restrictions to NLA operations, resulting in loss of airside capacity, or even preventing the NLA from operating there; (3) where an airline requires an exclusive[3] terminal for its NLA operations.

In any case, a pier configuration should be selected such that some performance criteria are optimized. Of those criteria, the most widely used is the average passenger walking distance. Wirasinghe et al [1987] proposed a method to determine the optimal number of parallel equal-length pier-fingers to minimize walking distance. Bandara & Wirasinghe [1992] evaluated the mean walking distance for several terminal concepts and determined the optimal terminal geometry in terms of the number of piers. Robusté [1991] analyzed several centralized hub terminal layouts, determining the walking distance for each of them and using it to determine the best geometry for the terminal. This work was expanded to include baggage handling by Robusté & Daganzo [1991]. All these works have a common drawback: they assume all gates are of the same type and size, which is very often not true. In the case of an NLA terminal, the specific location of the NLA gates in the terminal will have a significant influence in the overall walking distance.

This paper will analyze the case of a pier terminal designed to accommodate one or more NLA. It is assumed that the pier will have two types of gates: NLA and Conventional Jets (CJ), and that the number of gates of each type has

[3] Exclusive, in this case, means the airline will be the only one to operate in the terminal. The airline might mix NLA and CJ operations.

been previously determined. The objective of this paper is to determine where in the pier the NLA gates should be located. This work is part of a set of models and techniques to analyze the impact of the NLA on all aspects of airport terminal planning and operation [Barros, 2000], such as the determination of the gate requirement, the size of the departure lounge [Barros & Wirasinghe, 1998b], baggage handling and claiming, check-in, customs and security check operations.

Pier Configurations for 1 NLA Gate

As the market for NLA is predicted to be fairly small for some time ahead, it is very likely that many airports will not need more than one NLA gate. In this case, the problem is to find the best location for this sole NLA gate in the pier.

In this work, the criterion used to define the optimal location of the NLA gate is the overall average walking distance of NLA passengers. For one or two NLA gates only, the effect of the location of these gates on the walking distance of non-NLA-related passengers can be assumed to be negligible. The model does not take into consideration possible existing terminal and apron design constraints, which might preclude the NLA from parking at certain areas. If this happens, then the NLA should be parked where allowed by the design constraints.

In the case of 1 NLA position only, two types of passengers with common characteristics can be identified: hub transfers to conventional jets and originating/terminating/non-hub (OTNH) transfers. Hub transfers are passengers who transfer directly from one aircraft to another, where both aircraft are parked at the pier under consideration. The second group, OTNH transfers, embraces arriving passengers who have to leave the pier either for the main terminal or for another concourse, and departing passengers who either have checked in at the main terminal or have arrived on a flight that docked at another concourse. In both cases, passengers have to walk between the pier's main entrance and the aircraft. The walking distances for these passengers will therefore be determined by the location of the NLA gate with respect to the main entrance. Note that non-hub transfers whose both arriving and departing flights are docked at the pier under consideration have to walk both from the aircraft to the entrance and vice-versa, but only the NLA-related part of their walking will be of importance to the problem.

In most known cases, the pier entrance is either located at one end or at the pier center. The former is the case of pier-finger terminals, whereas the latter is more common in remote piers with underground access to the main terminal. Figure 1 shows a schematic of a pier terminal, with the two possible locations for the pier entrance.

<u>Pier with Entrance in the Middle</u>

Airports such as Atlanta and Denver have a number of remote parallel piers with access to the main terminal provided through the use of Automated

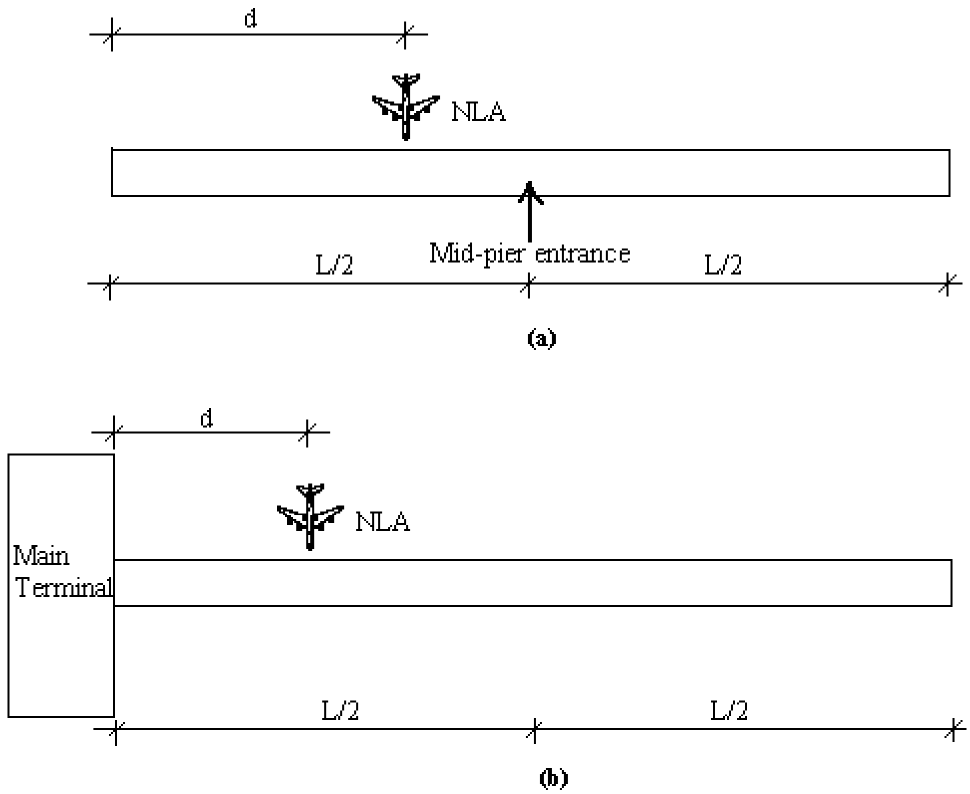

Figure 1: Pier configuration for 1 NLA
(a) Mid-pier entrance
(b) Pier-end entrance

People Movers (APM), where the APM stations are located at the pier center. The new Northwest Airlines terminal in Detroit is an example of the main terminal attached to the center of the pier. In both cases, OTNH passengers have to pass through the pier center, whereas hub transfers can move directly between the NLA and the CJ.

Let us consider the two extreme cases of proportions of transfers from the NLA: no transfers at all, and all transfers. In the first case, all passengers would be moving from the NLA to the pier entrance; therefore the location that minimizes walking distance for these passengers would be as close as possible to the entrance. In the second case, the whole NLA load would be transferring to CJ's, thus the location of the NLA in the middle of the pier would yield the minimal walking distance. Clearly, the best place to put the NLA gate would be as close as possible to the pier middle, independent of the proportion of transfers. Still, this will be proven mathematically, as this will provide the basis for the evaluation of the cases in which there will be more than one NLA.

Let L be the length of the pier; d be the distance from one of the pier ends to the NLA position; and p_T be the proportion of NLA passengers who are hub transfers – i.e. the proportion of NLA passenger who will transfer directly to a conventional jet docked at the pier. The problem then is to find the value of d as a function of L and p_T that minimizes the overall average walking distance.

OTNH passengers have to walk between the NLA gate and the center of the pier – where the pier entrance is located, whereas hub transfers walk directly between the NLA and the CJ. Assuming the hub transfers to CJ's are equally distributed along the pier length, and approaching both the location of the NLA position and of the destination aircraft to continuous variables, then the average walking distance within the pier for all passengers is

$$W = p_T \frac{d^2 + (L-d)^2}{2L} + p_N W_N + (1 - p_T - p_N)(L/2 - d) \tag{1}$$

where p_N and W_N are respectively the proportion of transfers between NLA and the corresponding walking distance for those transfers. Both equal zero for 1 NLA gate only.

Outside of the pier under consideration, OTNH passengers have more walking to do: to and from curbsides, parking lots, check-in counters, security checks, customs, and baggage claims. The walking distance related to these activities depends on the location of the pier with respect to the other terminal components, the type of connection between them, and the configuration of the main terminal. However, the walking distances outside of the pier under consideration do not depend on the pier configuration. Therefore, they will not impact the choice of the best gate arrangement within the pier.

With no constraints, the overall average walking distance W reaches its minimum when the value of d is set such that the partial derivative of W with respect to d – denoted by $\partial W/\partial d$ – equals zero. It can be shown that, for $0 \le d \le L/2$ and p_T and p_N ranging from 0 to 1, this derivative is always non-positive, which means W decreases with d. Therefore, W is minimum at $d = L/2$, with a consequent walking distance

$$W_{\min} = \frac{p_T L}{4} \tag{2}$$

In other words, for 1 NLA gate only and the pier entrance located in the middle of the pier, the best location of this NLA gate will be as close as possible to the middle of the pier. Note that this conclusion does not depend on the proportion of hub transfers p_T.

Pier with Entrance at One End

Pier-finger terminals like Calgary International Airport and Baltimore/Washington are connected to the main terminal through an entrance located at one end of the pier. Hub transfers will still be able to walk directly between the NLA and the conventional jet. OTNH passengers, however, will have to move between the NLA and the end of the pier.

For a pier with entrance at one end, the walking distance for hub transfers will remain the same as for a pier with entrance in the middle. As to the OTNH passengers' walking distance, it will now be the distance between the NLA gate and the end of the pier where the entrance is located. Therefore

$$W = p_T \frac{d^2 + (L-d)^2}{2L} + p_N W_N + (1 - p_T - p_N)d \tag{3}$$

For $p_T \leq (1 - p_N)/2$ it can be shown that $\partial W/\partial d$ is always non-negative, which means W is a crescent function of d. Hence W is minimum when d is minimum, i.e. when $d = 0$. The minimal walking distance in this case is

$$W_{\min} = \frac{p_T L}{2} \tag{4}$$

For $p_T > (1 - p_N)/2$, $\partial W/\partial d$ could be either positive or negative, thus W is minimum when the value of d is such that $\partial W/\partial d$ equals zero. Setting $\partial W/\partial d$ to zero and solving for d, we find

$$d = \frac{L}{2}\left[1 - \frac{(1 - p_T - p_N)}{p_T}\right] \tag{5}$$

This solution yields an average walking distance given by

$$W_{\min} = \left(\frac{2p_N(1-2p_T) + 4p_T - p_N^2 - 2p_T^2 - 1}{4p_T}\right)L \tag{6}$$

If the whole load of the NLA is comprised of hub transfers, then the NLA should be located at the pier center, and the average walking distance will be the average walking distance of NLA hub transfers only.

Figure 2 summarizes the optimal location of the NLA gate as a proportion of the terminal length, L, and as a function of the proportion of transfers, p_T.

The optimal location of the NLA gate and the correspondent average walking distance in the case of pier-end entrance are obviously very sensitive to the proportion of transfers to CJ's, p_T. For example, if the terminal is planned for

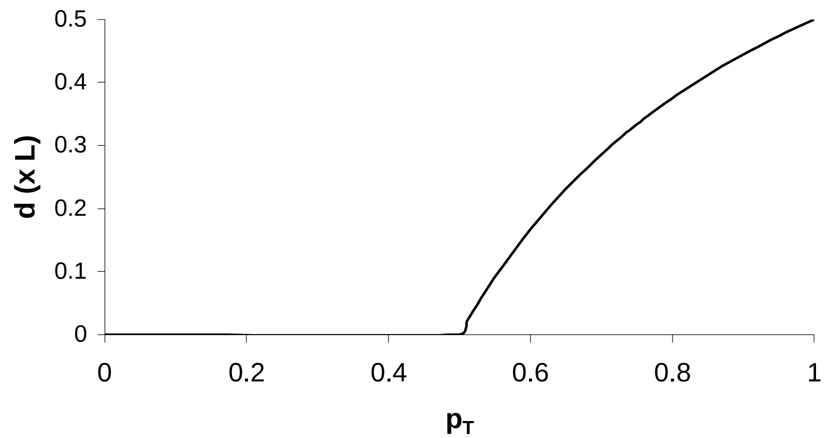

Figure 2: Optimal NLA gate location for the pier-end entrance case

50% transfers, and the actual proportion of transfers turns out to be 60%, then the average walking distance will be 20% higher than what it could have been, had the NLA gate location been determined for the correct transfers rate. This is a serious problem for airport planners, as the actual transfer rate is hardly known in advance. However, it is clear from the results above that, whatever the proportion of transfers, the NLA gate must be located in the pier half where the entrance is located. This conclusion rules out the location of the NLA gate at the edge of a pier-finger terminal, for instance – provided the goal is to minimize walking distance and no other constraints exist.

Pier Configurations for 2 NLA Gates

Piers that are expected to have two NLA docked simultaneously at any given time will, of course, need two NLA positions. These two NLA gates can be placed on opposite sides of the pier, facing each other as illustrated in Figure 3-a, or could be offset such that there is a distance S along the pier axis between the two positions, as shown in Figure 3-b. The distance S is assumed to be not smaller than a minimum S_{min}, which must be no less than the sum of the NLA wingspan and the minimal wing-tip-to-wing-tip distance.

The choice between the configurations shown in Figure 3 will depend on several factors. Putting the two NLA on opposite sides of the pier as in Figure 3-a has the advantage of allowing a very short walking distance between the two aircraft. This advantage may be especially significant when a high proportion of the NLA passengers transfer to another NLA. However, existing apron configuration constraints may allow only one pier side to be used for NLA operations. Besides, mobile ramp service equipment that is to be shared by the two gates can be much more easily moved between the gates if they are located side by side.

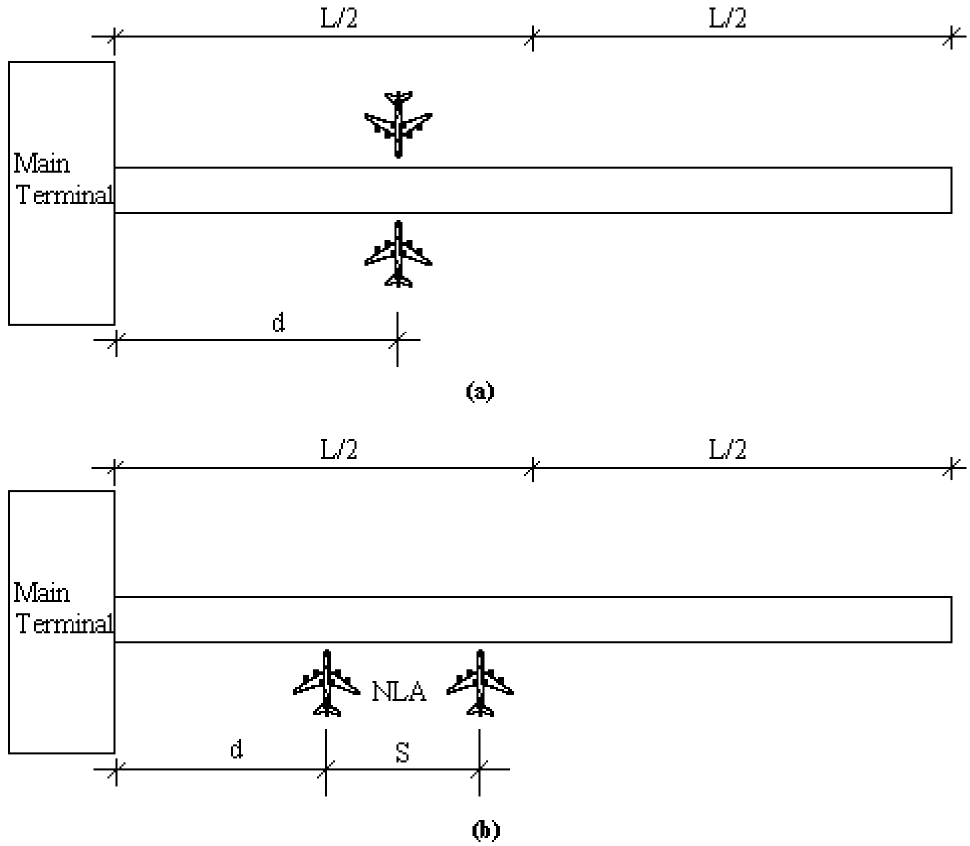

Figure 3: Pier Configuration for 2 NLA gates:
(a) on opposite sides of the pier;
(b) on the same side of the pier, offset by a distance *S*.

The main difference in the formulation of the walking distances of 2 NLA gates when compared to 1 NLA is that, for 2 NLA, there will be passengers transferring from one NLA to another. The proportion of these passengers and their respective walking distance will have an important role in the determination of the optimal location for the NLA gates. It is assumed that the amount of passengers and the proportions of transfers will be the same for both NLA positions. Other than that, the same assumptions made for the case of 1 NLA gate will be made for 2. The problem then is to find the values of d and S that minimize the overall passenger walking distance.

Two NLA Gates on Opposite Sides of the Pier

If the two NLA gates are located at the same point in the terminal but on opposite sides of the pier, facing each other as shown in Figure 3-a, then the problem is similar to the one with only one NLA gate and the same equations apply. The walking distance between the two NLA gates is negligible and will be assumed to equal zero in this analysis.

For a pier with entrance in the middle, it has been shown that the optimal location for the NLA gates depends neither on the proportion of CJ transfers, p_T, nor on the proportion of transfers between NLA, p_N. Therefore, the optimal location for the NLA gates is the same as for 1 NLA gate, i.e. as close as possible to the pier center, with the average walking distance given in Equation 2.

In the case of the entrance being at one of the pier edges, it has also been shown that, for $p_T \leq (1 - p_N)/2$, the best place to put the NLA gate is as close as possible to the entrance. However, if $p_T > (1 - p_N)/2$, then the NLA gate should be located at a distance d from the entrance, with d given in Equation 5 and average walking distance given in Equation 6. Mathematically, the only difference to the 1 NLA case is that now p_N may be greater than zero.

<u>Pier with Entrance at One End</u>

Assuming hub transfers to CJ's are equally distributed along the terminal length, the average walking distance within the pier for all passengers is

$$W_T = p_T \frac{d^2 + (L-d)^2 + (d+S)^2 + (L-d-S)^2}{4L} + p_N S + (1 - p_T - p_N)(d + \frac{S}{2}) \quad (7)$$

Let S' and d' be the values assumed respectively by S and d that yield the minimal walking distance. The search for the minimal value of W within its domain yields the results shown in Table 1. It can be seen from that table that the optimal solution requires the location of the two NLA gates to be separated by the minimal distance S_{min}. The NLA gate closer to the entrance should either be at the pier edge or at the distance d' according to the relationship given in Table 1.

<u>Pier with Entrance in the Middle</u>

The walking distances for passengers transferring to CJ's and to other NLA remain the same as for the case when the pier entrance is located at one of the pier ends. For OTNH passengers, however, the average walking distance will depend on whether the two NLA gates are on the same half of the pier or on opposite halves.

The values S' and d' that yield the minimal walking distance are shown in Table 2. The optimal solution is to have both gates symmetrically located around the pier center, separated by the minimal distance S_{min}.

Pier Configurations for 3 or More NLA

Should a pier terminal be designed to accommodate more than 2 NLA, the error introduced by the approach to continuously distributed passengers along the pier may become undesirably high. In this case, it will be better to use a discrete approach that takes into account the space occupied by each gate position and the

Table 1: Optimal solution for 2 NLA gates and pier-end entrance

Condition	*d* ¢	*S* ¢	$W_{\min}$
$p_T > \dfrac{(1-p_N)}{2[1-S_{\min}/L]}$	$\left[1-\dfrac{1-p_N}{2p_T}\right]L-S_{\min}$	$S_{\min}$	$\left[1-\dfrac{p_T}{2}-p_N-\dfrac{(1-p_N)^2}{4p_T}\right]L+$ $+\left[\dfrac{p_T}{4}\dfrac{S_{\min}}{L}+p_N\right]S_{\min}$
$p_T \le \dfrac{(1-p_N)}{2[1-S_{\min}/L]}$	0	$S_{\min}$	$\dfrac{p_T}{4L}\left[L^2+S_{\min}^2+(L-S_{\min})^2\right]+$ $+\dfrac{(1-p_T+p_N)}{2}S_{\min}$

Table 2: Optimal solution for 2 NLA gates and mid-pier entrance

Condition	*d* ¢	*S* ¢	$W_{\min}$
$\forall\, p_T, p_N, S_{\min}, L$	$\dfrac{L-S_{\min}}{2}$	$S_{\min}$	$\left[1-\dfrac{p_T}{2}-p_N-\dfrac{(1-p_N)^2}{4p_T}\right]L+$ $+\left[\dfrac{p_T}{4}\dfrac{S_{\min}}{L}+p_N\right]S_{\min}$

exact location of these gates in the pier, as well as the exact walking distance for CJ passengers. Although for the purpose of this work the objective function is to minimize walking distance, other performance criteria – such as baggage handling – can also be added.

For the purpose of this work, we will assume that both CJ and NLA gates will be provided in pairs, positioned at the same point in the pier, but located on opposite pier faces. This assumption will greatly simplify the formulation of the walking distances and will have little effect on the configuration of large terminals (20 gates or more). Figure 4 shows the general configuration of a pier terminal. The terminal configuration can be described by the set $n = \{n_1, n_2, \ldots, n_{N/2}\}$ of pairs of gate positions that will be reserved to NLA, where N is the total number of NLA gates.

The average walking distance within the pier is given by:

$$W = r_N \sum_k P_{Nk} W_{Nk} + (1-r_N) \sum_k P_{Ck} W_{Ck} \tag{8}$$

where:

k = {NLA, CJ, main entrance};
P_{Nk} = proportion of NLA passengers who walk to gate type k;
P_{Ck} = proportion of CJ passengers who walk to gate type k;
W_{Nk} = mean walking distance for passengers walking from NLA to gate type k;

W_{Ck} = mean walking distance for passengers walking from CJ to gate type k;

r_N = the fraction of the total passengers who arrive by NLA.

In the long run, it can be assumed that the total number of enplaning passengers equals the total number of deplaning passengers. Under this assumption, the total number of passengers transferring from NLA to CJ's must equal the number of passengers that transfer the other way around. Therefore

$$r_N P_{NC} = (1 - r_N) P_{CN} \tag{9}$$

Solving for P_{CN}, we find

$$P_{CN} = \frac{r_N}{(1 - r_N)} P_{NC} \tag{10}$$

If P_{CM} and P_{NC} are given, then the proportion of CJ passengers transferring to other CJ's, P_{RR}, will be

$$P_{CC} = 1 - P_{CM} - P_{CN} \tag{11}$$

Therefore, P_{CC} and P_{CN} are internal parameters in the model, whereas the proportions r_N, P_{NN}, P_{NC}, P_{NM} and P_{CM} will be external parameters to be input in the model by the planner.

The equations for the walking distances vary according to the terminal concept. These equations are found by determining the walking distance between every pair of gate positions (i, j) and averaging for the appropriate movement type (NLA to CJ, CJ to entrance, and so on). The inputs for the model are: the total number of gates, m; the number of NLA gates, N; the location of the pier entrance, represented by the distance from the entrance to gate position 1; the fraction of passengers who arrive by NLA, r_N; and the proportions of each movement type. The representation of the pier entrance location using the distance from the edge allows the analysis of special scenarios – e.g. when a pier with a mid-pier entrance has to be expanded in just one direction due to existing physical constraints. The output of the model is the order in which the gates are to be arranged along the pier, represented by the set n as explained above.

Optimization

The search for the optimal configuration – where the objective, for the purpose of this work, is the walking distance implied by a given configuration – is a combinatorial optimization problem of the NP-complete type. The exact optimal solution for this type of problems can only be found by analyzing a very large number of possible configurations. Such exhaustive analysis, however, can have a

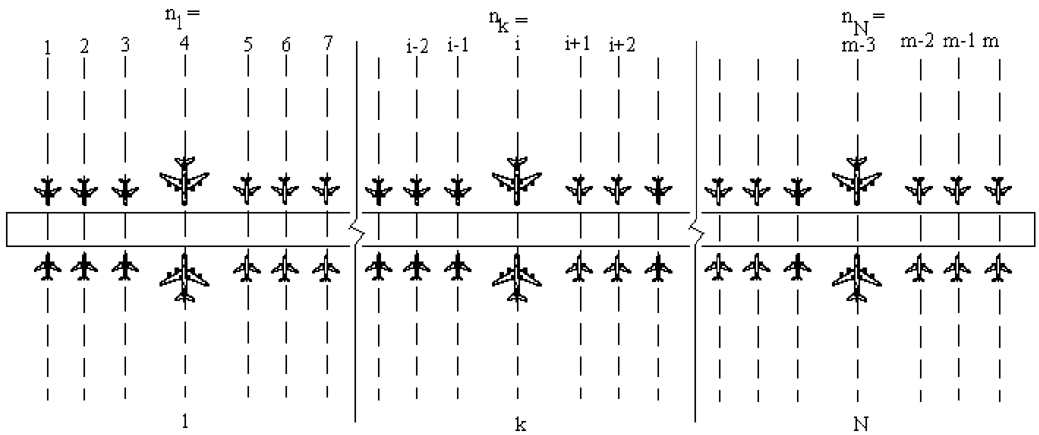

Figure 4: Description of a pier terminal configuration

prohibitive time or computing costs for a large number of gates. Nonetheless, heuristic methods are available that can provide a very good local optimum without consuming too much of computational resources.

One heuristic that has been used in some air transportation applications [Robusté & Daganzo, 1991; Lucic & Teodorovic, 1999] is *simulated annealing* [Kirkpatrick et al, 1983]. This is an iterative method in which, for each iteration, a perturbation is performed on the current solution, generating a new one. The new solution is accepted with probability 1 if it is better than the old solution and with probability *p* if it is worse. The process is performed according to a *temperature schedule* – an analogy to the physical process of annealing. The search for the optimum is done in phases, where the probability *p* – which is a function of the *temperature* – is larger for the early phases and is reduced as the process progresses from one phase to another. The use of this probability *p* allows the process to escape from local optimums and search for optimums in other regions, always keeping the best solution found. If the perturbation is such that it does not prevent any possible solution from being tested, then the process leads to a state of system equilibrium that yields a near-optimal solution.

For the problem of locating NLA positions in a pier terminal, simulated annealing seems to be an adequate technique. The perturbation in the current solution could be done by randomly selecting an element n_k from the set n and either increasing or decreasing its value in one unit, if possible. The temperature schedule should be set to allow the system to "cool down" and "crystallize" smoothly and at the minimum processing time. A good solution, that offers a balance between an acceptable deviation from the optimum and a low computing time, can then be found using this method.

A program in C++ was written to evaluate the optimal gate arrangement for a pier terminal under the aforementioned conditions, using simulated annealing. An example is presented for a pier-finger with a total of 20 gates, of which 6 are NLA gates and the others are CJ gates, and input parameters given in Table 3. Figure 5, Figure 6 and Figure 7 show the optimal gate arrangement for different values of r_N.

Conclusions

For piers with only one or two NLA positions, the approximation of the problem to a continuous distribution of passengers along the pier provides an accurate, easy to understand insight to the problem of locating those gates in the pier. Four basic scenarios were studied using this approach, combining the location of the pier entrance – at one of the pier ends or at the pier center – and the number of NLA positions – one or two.

Table 3: Input parameters for the numerical example

NLA maximum wingspan (m)	80
CJ maximum wingspan (m)	55
Wing-tip-to-wing-tip clearance (m)	7
r_N	0.4
P_{NN}	0.2
P_{NC}	0.4
P_{NM}	0.4
P_{RM}	0.4

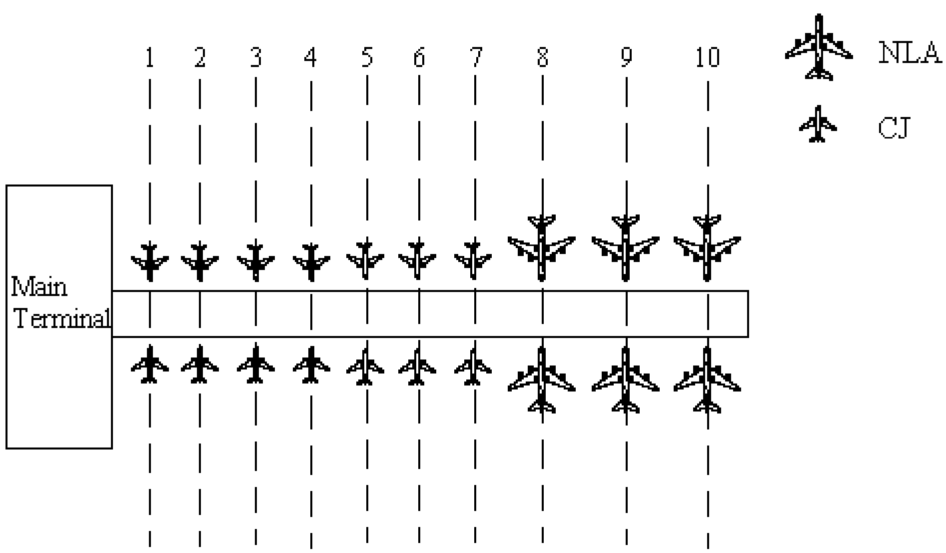

Figure 5: Optimal gate arrangement for the numerical example r_N = 0.3

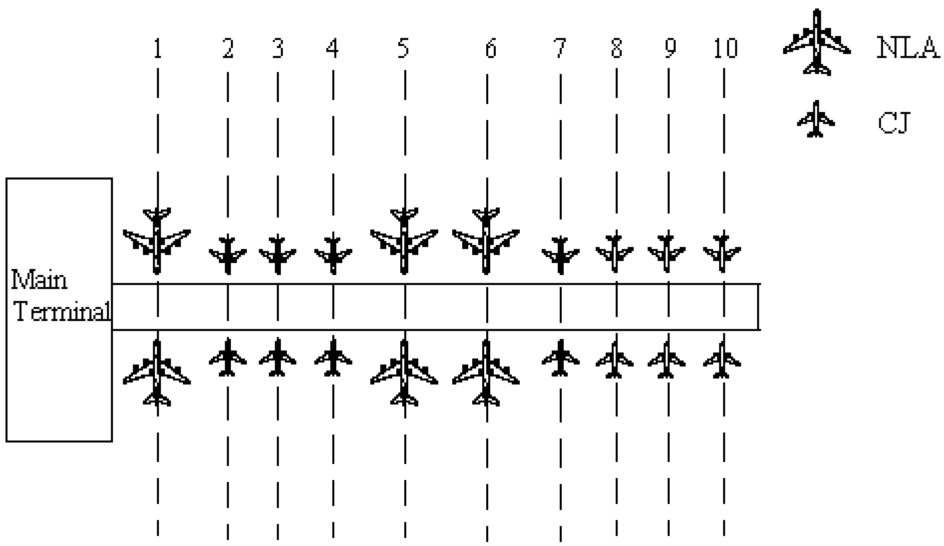

Figure 6: Optimal gate arrangement for the numerical example
r_N = 0.4

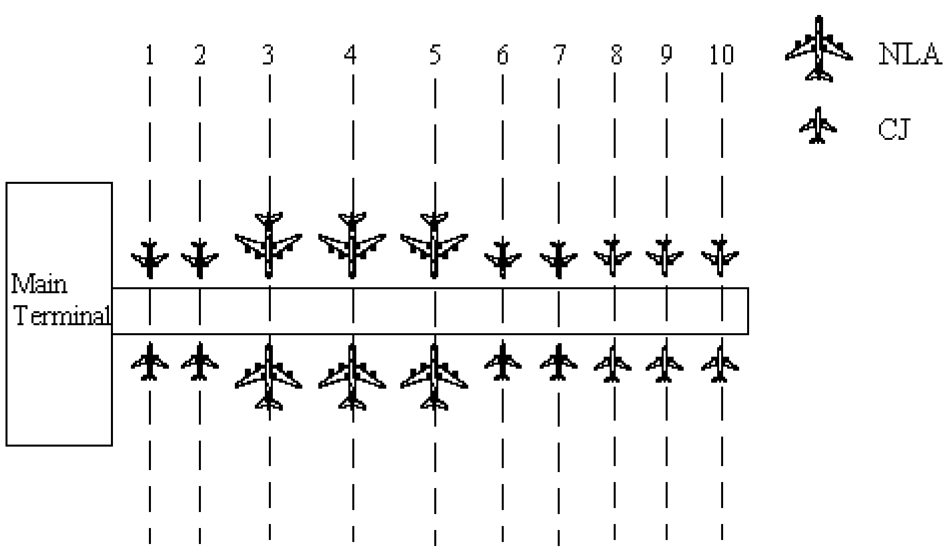

Figure 7: Optimal gate arrangement for the numerical example
r_N = 0.6

In the case of either a single NLA gate or two gates facing each other and entrance at the pier center, the best location is as close as possible to the pier center. If the pier entrance is located at one end of the pier, the best location will vary according to the proportion of passengers who are hub transfers. However, regardless of the proportion of transfers, the NLA gate position should be located in the same pier half as the entrance. These conclusions do not take into account possible existing apron and terminal design constraints.

For two NLA gates positioned on the same side of the pier, it has been shown that they should be located side by side at the pier center, if that is where the entrance is. On the other hand, if the pier entrance is located at one of the pier ends, then the best location for the NLA gates will depend on the proportions of hub transfers and on the minimal separation between those gates, as they should also be put side by side.

A model to exactly locate more than two NLA gates in pier terminals using simulated annealing has been proposed. This model can be expanded for application to other terminal concepts by determining the correct functions for walking distance for each different terminal concept. It can also be adapted to include other criteria in the objective function, such as baggage operations.

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