ARTIGO

EVALUATION OF THE NUMBER OF GATE POSITIONS AT AN AIRPORT TERMINAL USING A SHARED COMMON AREA

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RESUMO

Este trabalho descreve um modelo analítico para determinação do número de portões de embarque em um terminal aeroportuário para fins de planejamento. O modelo calcula o número de até três diferentes tipos de portões, buscando minimizar uma função custo que inclui custos de construção do terminal, de instalação e manutenção dos portões e de atrasos impostos às aeronaves. O modelo também leva em consideração o uso de uma área comum para portões de diferentes tipos. Esta área comum é usada tanto por aeronaves grandes como por aeronaves pequenas durante seus respectivos picos diários principais. Com esta área comum, consegue-se uma economia considerável de espaço no terminal, usando-se o espaço disponível de maneira mais eficiente.

ABSTRACT

A model to evaluate the number of gates at an airport terminal for planning purposes is presented. The model calculates the number of gates of up to three different types, seeking to minimize a cost function that includes terminal construction, gate installation and operation, and aircraft delay costs. The model also takes into account the sharing of a common area in the terminal by gates of different

types. This common area is used by both large and smaller aircraft during their respective main daily peaks. With this space sharing, a considerable amount of terminal space can be saved, making more efficient use of the space provided.

1. INTRODUCTION

The number of gate positions at an airport terminal is usually one of the first variables to be evaluated in the process of airport terminal planning. Terminal concept and configuration, apron layout, walking distances, taxiway distances and airside delays will ultimately depend on the amount of gates provided. In the early stages of the terminal planning process, it is necessary to have an accurate estimate of how many gate positions must be provided to meet the demand.

Several factors influence the choice of the number of gates, the main ones being ultimately related to the balance between supply – the gate system – and demand – the aircraft. The supply level is mainly determined by the gate occupancy time, whereas the demand level is given by the aircraft arrival rates. Other factors are the demand characteristics – such as aircraft mix and proportion of regular/charter flights – airline schedules and gate usage policy.

During peak hours, if the aircraft arrival rate exceeds the gate capacity, then delays will be imposed to aircraft unable to find an empty position. This situation can be avoided by a sufficiently large number of gates; however, more gates imply higher construction, installation and maintenance costs. Therefore, it may be desirable to allow a certain level of delay such that an optimum tradeoff between gate costs and aircraft delay costs is achieved.

If airline schedules are available, the number of gates can be derived directly from the schedules. A simple simulation model can be built with as much detail as allowed by the data available. Analytical models derived from the schedules are also possible. Based on an early work by Steuart (1974), Hassounah and Steuart (1993) developed a model that evaluates the demand for aircraft gates based on deviations from the schedule. For each flight *i* on the schedule, a

Bernoulli variable $Y_i(t)$ representing the occupancy of a gate by that flight at a given time t is defined. The model determines the distribution of that Bernoulli variable as a function of time and calculates the number of gates at anytime as the sum of the Bernoulli variables for all flights.

Unfortunately, airline schedules are seldom available in the early stages of the terminal planning. In that case, the best information available will be in the form of aircraft arrival rates. As this information is not enough to build a simulation model, analytical models that use the aircraft arrival rate as input must be used.

A simple approach used by Horonjeff & McKelvey (1994) is the calculation of the number of gates based on a utilization factor U that accounts for the impossibility of keeping a gate occupied 100% of the time. In this approach, the total number of gate-hours available – corrected by the application of the utilization factor – is set to at least exceed the number of gate-hours demanded, i.e.

$$U \cdot N \geq T \cdot C \qquad (1)$$

where T: mean gate occupancy time;
C: gate system design capacity (aircraft/hour).

The main drawback of the application of a utilization factor is the fact that this factor is very hard to determine in advance and the number of gates that satisfies Equation 1 is very sensitive to the utilization factor. Besides, this model does not account for the effects of allowing some level of delay to save in gate costs.

To overcome these disadvantages, Bandara & Wirasinghe (1988, 1990) have developed two analytical models for the number of gate positions using different approaches: level of service and minimum cost. The level of service approach consists in evaluating the probability distribution of the number of gates G and then finding the value g that will allow a desired level of reliability, i.e. the percentage of time $1 - \alpha$ that arriving aircraft will find a position available. The value of G is given by

$$G = A(T + S) \qquad (2)$$

where A: aircraft arrival rate (aircraft/hour);
T: mean gate occupancy time (hours);
S: time gap between gate occupancies to allow for aircraft maneuvering (hours).

In Equation 2, A, T and S are all random variables, which means G is also a random variable. Numerical methods or field data can be used to determine the exact distribution of G. This allows us to choose the number of gates g based on the level of reliability 1 - α, such that

$$P(G \leq g) = 1 - \alpha \qquad (3)$$

For long term planning, Bandara & Wirasinghe (1990) seek a balance between the cost of providing gates and the cost of delays caused to aircraft by lack of available positions. The total cost function is

$$C = G\,k + W\,d \qquad (4)$$

where G: number of gates;
W: total deterministic delay imposed to aircraft;
k: cost of a gate position;
d: cost per unit of delay time.

Both G and W can be expressed as functions of the service rate A. G is calculated as in Equation 2. Newell (1982) and Bandara & Wirasinghe (1990) have developed expressions for the deterministic delay caused by an arrival peak exceeding the service rate with a parabolic and a triangular shape, respectively. Substituting for G and W in Equation 4, one can find the optimal service rate that minimizes the cost of the terminal, C, by setting its first derivative to zero.

A common feature of the methodologies described above is that they can only be applied to gates of the same type. For different gate types, the models must be applied separately for each type. The models overlook the possibility of saving terminal space by sharing some terminal area among different types of aircraft, as suggested by

IATA (1995). This space saving can be more significant if the peaks for different aircraft types occur at different times of the day – as illustrated for Los Angeles International Airport in Figure 1 – and when very large aircraft such as the New Large Aircraft (NLA) are mixed with smaller ones (Barros & Wirasinghe, 1997, 1998b). In this case, a certain amount of terminal area could be assigned as a common area, to be used by, say, wide-bodied (WB) aircraft during wide-bodied peaks and by narrow-bodied (NB) aircraft during narrow-bodied peaks. A conceptual illustration of this space sharing is shown in Figure 2.

2. SPACE SHARING MODEL

Let us assume that there will be three types of gates: conventional jet (CJ) gates, requiring l_C meters of airside frontage per gate; wide-body gates (WB), which require l_W meters of airside frontage each; and NLA gates, with an airside frontage requirement of l_N meters per gate. If both NLA and WB peaks occur during the same time period as the CJ peak, then the determination of both the number of gates and the terminal length is done separately for each gate type, and the total terminal airside frontage will equal the sum of the terminal length requirements for each gate type, i.e.

$$L = l_N G_N + l_W G_W + l_C G_C \qquad (5)$$

where G_N, G_W and G_C are the number of NLA, WB and CJ gates, respectively. In this case, there will be no shared space between the three gate types, and consequently there will be no positions being blocked by the simultaneous use of others.

In many cases, however, arrival peaks for different gate types occur at different times of the day. Figure 1 shows arrivals at Los Angeles International Airport. It can be seen that the Conventional Jets main peak is dissociated from the Wide-Bodies main peak. For the purpose of this work it will be assumed that NLA peaks will occur simultaneously with WB peaks. This assumption seems reasonable as NLA are being designed to operate on routes currently served by WB jets.

The number of positions necessary to accommodate the demand for a given gate type will be determined by that type's peak; however, the number of positions provided during off-peak and secondary-peak periods could be lower. If different gate types could share the same space in a terminal as illustrated in Figure 2, then that space could be used as CJ gates during CJ peaks and as NLA/WB gates during NLA/WB peaks.

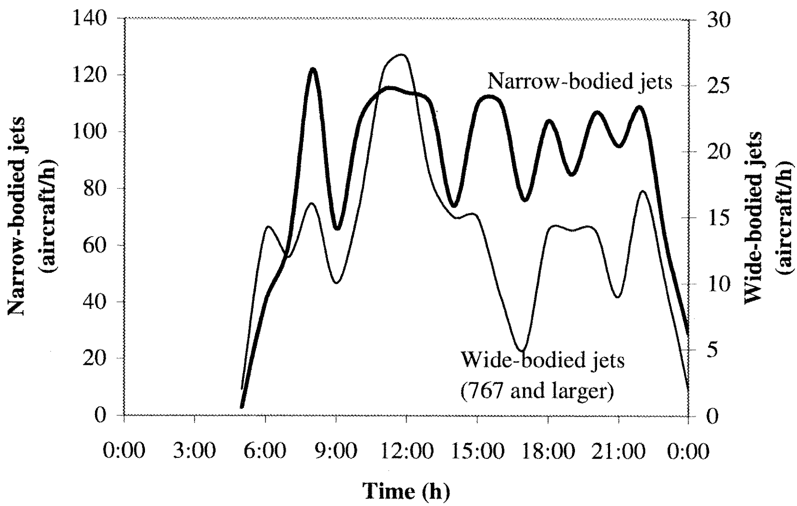

Figure 1: Narrow-bodied and wide-bodied arrivals at Los Angeles International Airport

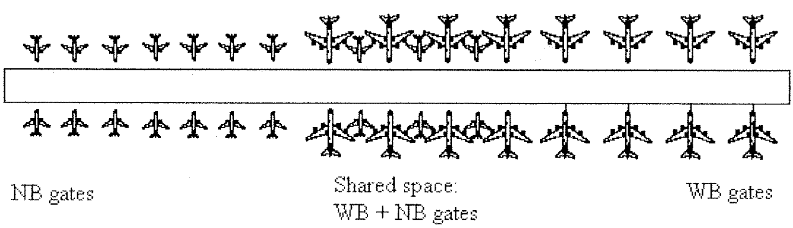

Figure 2: Wide-bodied and narrow-bodied jets sharing space at the terminal

Figure 3 illustrates the use of different gate service rates. In this example, there are two peak periods: the first is a NLA/WB peak with a correspondent secondary CJ peak, since NLA are expected to be used in hub operations, with a large amount of NLA passengers transferring to CJ's. During this period, the NLA and WB gate service rates would be at their maximum – μ_{N1} and μ_{W1} respectively – while CJ's could be serviced at a rate $\mu_{C1} < \mu_{C2}$. The main CJ peak, however, occurs at a different time, when NLA and WB arrivals are less frequent. Thus, the CJ maximum service rate, μ_{C2}, would occur during this main CJ peak, whereas NLA and WB could then be serviced at the rates $\mu_{N2} < \mu_{N1}$ and $\mu_{W2} < \mu_{W1}$ respectively.

The number of *available* gates for a given aircraft type *i* during the peak period *j*, AG_{ij}, can be evaluated using the Bandara & Wirasinghe (1990) equation

$$AG_{ij} = \mu_{ij}(T_i + S_i) \quad (6)$$

where T_i: the average gate occupancy time of aircraft type *i*;
S_i: the average time separation required between two consecutive gate occupancies to allow for aircraft maneuvering;
i: aircraft type; $i = \{CJ, WB, NLA\}$;
j: peak period; $j = \{1, 2\}$.

Let us define G_i as the number of *existing* gates for a given aircraft type *i* – regardless of whether they are available during a given peak period or not. G_i will then be the number of gates available during the most demanding period peak for that aircraft type,

$$G_i = \max(AG_{i1}, AG_{i2}) \quad (7)$$

By definition, the most demanding peak period for NLA and WB is 1, whereas for CJ it is 2, as illustrated in Figure 3. Therefore

$$G_N = \mu_{N1}(T_N + S_N) \quad (8)$$
$$G_W = \mu_{W1}(T_W + S_W) \quad (9)$$

$$G_C = \mu_{C2}(T_C + S_C) \quad (10)$$

The terminal airside frontage length for each peak period j will be the sum of frontage requirements for NLA, WB and CJ, i.e.:

$$L_j = \sum_i l_i AG_{ij} = \sum_i l_i \mu_{ij}(T_i + S_i), \quad j = \{1,2\} \quad (11)$$

where i represents aircraft types and j represents the peak period.

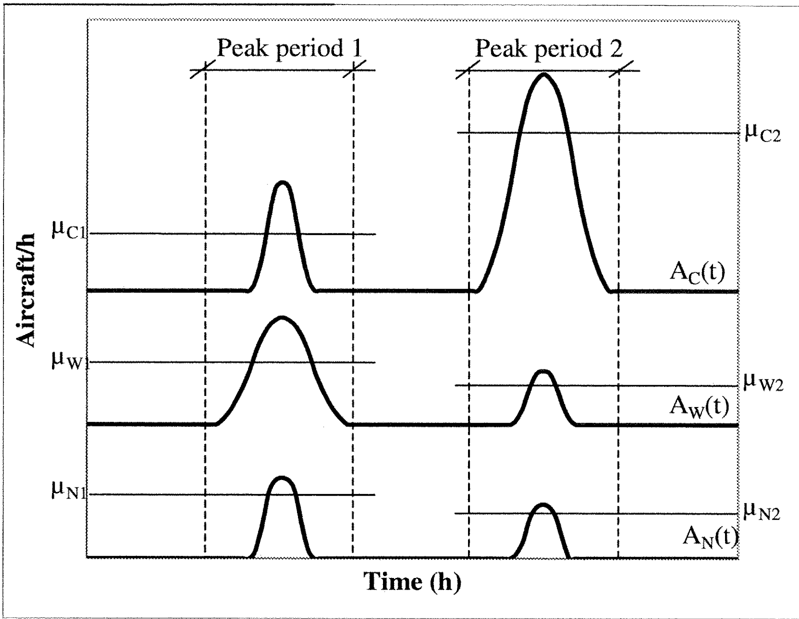

Figure 3: Different service rates for different arrival peaks on one day

Note that L_1 and L_2 could have different values. In that case, the final length L of the terminal frontage will be the greater of the two length requirements:

$$L = \max(L_1, L_2) \quad (12)$$

Since, by definition, $\mu_{N1} > \mu_{N2}$, $\mu_{W1} > \mu_{W2}$, and $\mu_{C1} < \mu_{C2}$, it becomes clear that the above terminal airside frontage requirements will be less than with no space sharing. Therefore, the use of shared space could reduce the final length of the terminal and, consequently, reduce its construction cost without imposing any further delays.

2.1. Operational Issues

The use of a common area for CJ, WB and NLA in the terminal will create a number of problems to the operation of the terminal that must be taken into account when implementing the space sharing model. This section will discuss the three main issues identified: the use of departure lounges by different gate types; the need to clear the gates in the common area of unwanted aircraft types before a peak period begins; and the separation of international and domestic passengers.

Should a part of the terminal area be used by CJ, WB and NLA – though not simultaneously – this area must be able to accommodate passengers of all aircraft types. The best way to do so would be through the use of common departure lounges as opposed to gate-dedicated lounges. Common lounges do not require any conversions from one aircraft type to another – passengers would simply arrive at the common lounge and settle near their assigned gate. Common lounges also have the advantage of saving a considerable amount of space when compared to separate lounges (Wirasinghe & Shehata, 1993; Horonjeff & McKelvey, 1994). To avoid confusion for passengers, gates sharing a same lounge should have the same number denomination, with slight variations to distinguish the gates – e.g. gates 25A, 25B and 25C would all be served by the same lounge.

If separate lounges for each gate are required – e.g. when security screening is done separately for each gate – then it is still possible to use the same area for both CJ and NLA by using mobile walls. A special arrangement may be necessary, however, to ensure that all passenger and airline services – such as washrooms and airline processing counters – are still provided for each lounge.

It cannot be forgotten that the total area required for CJ, WB and NLA lounges might be different. In addition, while NLA could make use of two-level boarding and lounges (Barros & Wirasinghe, 1998a), CJ and WB will most likely require single-level lounges. Hence the lounge area will probably have to be determined by the most restrictive of the three requirements.

During off-peak periods, the common CJ/WB/NLA area may be used for either type of aircraft as long as the proper wing-tip-to-wing-tip clearances are kept. In fact, depending on the terminal configuration and geometry, parking aircraft at the common area may even help reduce passenger walking, baggage transfer, and aircraft taxiing distances. However, when a CJ main peak period begins, it is mandatory that the common area be cleared of WB and NLA and vice-versa. To ensure this clearance, it is necessary to stop assigning aircraft of the opposite types long enough before the main peak period begins. If practical, it may even be useful to establish a time gap between the time of departure of the last aircraft and the beginning of the main peak period. For instance, if a WB/NLA peak starts at 10:00, then no CJ with an estimated departure time later than 9:30 should be assigned to a gate in the common area.

In many airports, the flow of international passengers must be separated from the domestic flow. Usually, this is done by creating international sections inside the terminal, to which only international passengers have access. Another solution that can be used when only international arrivals must be separated is forcing disembarking passengers to go either up or down a level as soon as they leave the plane and walking through a "sterile" corridor to the immigration and customs facilities (Steinert & Moore, 1993). International departures, in that case, are allowed to mix with domestic passengers.

If an international section is required for either WB or NLA operations, it is necessary to ensure there is no mixing of international and domestic flights in the CJ/WB/NLA common area. One way to do so is assigning only CJ that are international flights to the common area. This solution will not always be possible, as it would be necessary that the international CJ flights demand during the CJ main peak fit exactly the number of CJ gates in the common area. In this case, another solution would be the use of mobile walls.

This would allow the common area to be easily converted from a domestic section to an international section.

3. COST OF GATE REQUIREMENT

Three types of cost are imposed both by the number of gates for each gate type and the amount of space shared by them: 1) cost of gate installation and operation; 2) cost of terminal airside (pier) construction; and 3) cost of delays imposed to aircraft.

The first type of cost, cost of gate installation and operation, will be mainly a function of the type of gate – NLA, WB or CJ. The specific installation requirements, the type of loading bridge used, and any special equipment for the operation of the gate – such as the addition of a second floor for the NLA departure lounge – will determine its cost. If we assume that the daily cost of installation and operation per type i gate is a constant, k_i, then the total daily cost of type i gates is given by $k_i G_i$, where the number of type i gates G_i is given in Equation 7. The overall cost of gates will equal the sum of the costs for each gate type.

The cost of terminal airside construction can be assumed to be proportional to the total terminal airside frontage. The terminal airside is defined as the portion of the terminal beyond the security scrutiny, comprised of the gates, departure lounges, circulation areas and passenger amenities associated with the aircraft boarding/unboarding process, plus the apron. It does not include check-in, baggage claim, customs nor any other areas usually located in the main terminal.

The cost of terminal airside construction will include all capital costs associated with the civil construction of the terminal and the apron, excluding those associated with the gates, as mentioned above. Although NLA gates may require a double-level lounge, the cost of adding this second level can be included in the cost of gates. If a_f is the discounted daily cost per linear meter of terminal airside frontage, then the total daily cost of airside frontage will be $a_f L$.

Finally, the delay cost will depend on both the type of aircraft and on the amount of delays generated by the gate availability. Therefore, if d_i is the cost per unit of time of delay imposed to aircraft of type i, and W_i is the total deterministic delay imposed to type i aircraft due to lack of available gates, then the total daily cost of delay for type i aircraft is $d_i W_i$.

We are now ready to define the total daily cost imposed by the gate availability, C, which will be the sum of all three types of costs presented above:

$$C = \sum_i k_i G_i + a_f \ L + \sum_i d_i W_i \qquad (13)$$

The determination of the unitary costs k_i, a_f and d_i is beyond the scope of this work; hence they will be assumed to be known for the implementation of the model. Gate installation and operation costs and terminal construction costs are dependent of the number of gates and of the terminal length, respectively. Both can be evaluated as previously discussed. The third type of cost, delays imposed to aircraft, will require the evaluation of these delays.

3.1. Evaluation of the deterministic delays

It is known from queuing theory that the deterministic delay caused to aircraft is a function of both the arrival rates and service rates. If a peak j, where $j = \{1,2\}$, of an aircraft type i can be assumed to have an either parabolic or triangular shape, then the total aircraft deterministic delay for that peak will be a function of the maximum arrival rate A_{Mij}; the mean arrival rate $\bar{A}_i$; the time T_{0ij} during which the mean arrival rate is exceeded; and of the service rate. If the service rate exceeds the maximum arrival rate, there will be no delays imposed to aircraft. Otherwise, a queue will form when the arrival rate exceeds the service rate, and delays will occur. With two distinct peak periods on a day as illustrated in Figure 3, the total deterministic delays for both CJ and NLA can be written as:

$$W_i = \sum_j w(\mu_{ij}, A_{Mij}, \bar{A}_i, T_{0ij}), \quad i = \{\text{CJ, WB, NLA}\} \qquad (14)$$

To evaluate the total cost of gate availability, it is necessary to determine the amount of deterministic delay as a function of both the peak shape and the service rate during the peak time. Newell (1982) and Bandara & Wirasinghe (1990) have developed analytical expressions to determine delays as a function of service rate and both average and maximum arrival rates when the peak has either a parabolic or triangular shape, respectively. Figure 4 illustrates both cases. For the parabolic peak case,

$$w(\eta, A_M, \bar{A}, T_0) = \frac{9T_0^{\,2}(A_M - \eta)^2}{16(A_M - \bar{A})} \qquad (15)$$

and for the triangular peak case,

$$w(\eta, A_M, \bar{A}, T_0) = \frac{T_0^{\,2}(A_M - \eta)^3}{2\sqrt{2}(A_M - \bar{A})^2} \qquad (16)$$

where η: gate service rate for the duration of the peak.

It is assumed that a queue begins to form as soon as the arrival rate $A(t)$ exceeds the service rate η, and that the service rate is sufficiently higher than the mean arrival rate to guarantee that the queue vanishes before another one starts due to another peak. The latter condition is satisfied if (Bandara & Wirasinghe, 1990)

$$\eta \geq \frac{3}{4} A_M + \frac{1}{4} \bar{A} \qquad (17)$$

and

$$\eta \geq \frac{2}{2+\sqrt{2}} A_M + \frac{\sqrt{2}}{2+\sqrt{2}} \bar{A} \qquad (18)$$

for a parabolic and a triangular peak respectively. If the inequality corresponding to the shape of the peak is satisfied, then the queue will vanish within the peak duration T_0. The deterministic delays for each peak as illustrated in Figure 3 can be determined by substituting its own parameters into either Equation 15 or 16, according to the peak shape.

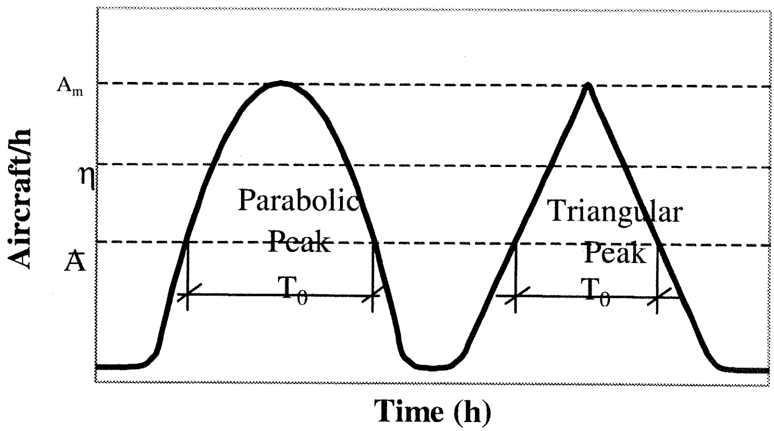

Figure 4: Parabolic and Triangular Shaped Peaks

When operational data show a peak with an undefined shape, it may be helpful to approximate it to a known form. Bandara & Wirasinghe (1990) suggest an approximation to either parabolic or triangular shapes with a 10% error for peaks with undefined shapes. If a measure of the area bounded by the arrival rate curve and the mean arrival rate line can be obtained, then if we let

$$E = \frac{A_M - \bar{A}}{\text{Area measured}} \qquad (19)$$

then the peak can be approximated by a triangle and a parabola if $1.75 < E < 2.25$ and $1.30 < E < 1.75$ respectively. In cases where the delay cannot be analytically determined, the use of either graphical or numerical techniques will be necessary.

4. COST MINIMIZATION

If the shapes and parameters of the arrival rate functions are known, and so are all the unit costs, unit frontage requirements, and average gate occupancy and separation time, then the total cost C becomes a function of the service rates only, as it can be seen when we substitute from Equation 14 in Equation 13:

$$C = \sum_{i} k_i G_i + a_f\, L + \sum_{i,j} d_i w(\mu_{ij}, A_{Mij}, \bar{A}_i, T_{0ij}) \qquad (20)$$

Since G_i is a function of the service rates μ_{ij}, and ultimately so is L, the problem then becomes to find the values for μ_{ij} that minimize the overall cost C, subject to the constraints of non-overlapping queues. Substituting for the peak parameters in Equations 17 and 18,

$$\mu_{ij} \geq \frac{3}{4} A_{Mij} + \frac{1}{4} \bar{A}_i,$$

for each (i, j) peak with a parabolic shape (21)

and

$$\mu_{ij} \geq \frac{2}{2+\sqrt{2}} A_{Mij} + \frac{\sqrt{2}}{2+\sqrt{2}} \bar{A}_i,$$

for each (i, j) peak with a triangular shape (22)

The problem above is a Non-Linear Programming (NLP) problem that can be solved with the use of any NLP optimization technique available and will yield optimal non-integer numbers of gates. To have an integer solution, it will be necessary to add the constraints that the variables G_{ij} must be integer. The problem then becomes a Mixed Integer/Non-Linear Programming (MINLP) problem and its results will be the number of gates for every peak-gate type pair that yield the minimum total cost.

5. NUMERICAL EXAMPLE

To illustrate the application of the models presented in this paper, let us consider the hypothetical example of an airport terminal under planning for servicing NLA, WB and CJ demands. The characteristics of the peaks, as well as the aircraft operational parameters, are given in Table 1. This table also gives the values of the costs used in this example. As the determination of these costs is beyond the scope of this work, fictitious values were used to produce this example – they should not be used as a reference.

The optimization was performed using the Microsoft Excel® Solver. To avoid getting stuck in a local optimum, several runs were performed, each with a different randomly generated initial solution. After each run, the solution found was compared to the best solution so far and was discarded if its cost was higher, or replaced the best solution if it yielded a lower cost. The resulting optimal numbers of gates are Table 2.

It can be seen in Table 2 that only a small delay is allowed to NLA aircraft during the NLA/WB peak (peak 1). Approximately 200 m of terminal frontage used for NLA/WB gates during peak 1 will be used by CJ gates during peak 2. That means 2 WB and 1 NLA positions will not be available during peak 2, whereas 5 extra CJ gates will be provided. In the end, that means 200 m of terminal frontage were saved. The way in which this space will be shared will depend on the terminal and apron configurations.

The cost of this solution, given in Table 2, is $100,800 a day. For comparison, the same example was run with a small modification in the model that eliminated space sharing. The results are shown in Table 3. The optimal solution in that case had a daily cost of $109,800, which means the use of a shared area in this example allowed an 8.2% saving in the overall cost of the terminal.

Table 1: Input parameters for the numerical example

	AIRCRAFT TYPE			
	GENERAL	NLA	WB	CJ
COSTS				
Cost of terminal construction ($ per meter of terminal frontage per day)	54			
Cost of gate installation and operation ($ per gate per day)		1109	670	564
Cost of delay imposed to aircraft ($1000 per hour of delay)		29.4	15.4	7.5
AIRCRAFT CHARACTERISTICS				
Terminal frontage requirement (meters per gate)		87.5	59.5	40.5
Gate turnaround time (hours)		1.483	1	0.667
PEAK PARAMETERS				
Peak 1				
Maximum arrival rate (aircraft per hour)		5	8	13
Average arrival rate (aircraft per hour)		1	3	8
T_0 (hours)		2	2	2
Peak 2				
Maximum arrival rate (aircraft per hour)		3	4	20
Average arrival rate (aircraft per hour)		1	3	8
T_0 (hours)		1	1	3

Table 2: Optimal number of gates with space sharing

	NLA		WB		CJ	
	Peak		Peak		Peak	
	1	2	1	2	1	2
Number of gates	7	5	8	4	9	14
Daily delay (hours)	0.044	0	0	0	0	0
Total daily cost ($1000)	100.8					
Shared space	202.5 m (5 CJ, 2 WB and 1 NLA gates)					

Table 3: Optimal number of gates with no space sharing

	NLA		WB		CJ	
	Peak		Peak		Peak	
	1	2	1	2	1	2
Number of gates	7	7	8	8	13	13
Daily delay (minutes)	2.66	0	0	0	0	6.33
Total daily cost ($1000)	109.8					

6. CONCLUSIONS

Two common problems in airport terminal planning were addressed in this paper: the determination of the number of gates to be provided and the sharing of space by gates of different types for better utilization of resources. These problems gain a new dimension under the light of the introduction of NLA.

It has been shown that the use of common areas by NLA, WB and CJ gates can reduce the cost of construction and consequently the overall cost of the terminal. This space sharing can only be done, however, if the main peaks for all types are sufficiently separated in time, so that there is no overlapping of the respective queues. The implementation of proper operational policies will allow for this space sharing without any major drawbacks in terminal operations.

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