INTRODUCTION

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In civil aviation, many problems arise in the interface of the aircraft with the airport and its environs. One facet of Transportation Research Board (TRB) aviation activity concerns the development and application of technology for analyzing and improving this interface, particularly on the ground, to provide a basis for decisions involving the design, construction and operation of aircraft and airports which are compatible, well integrated and cost effective.

In 1981, a TRB-sponsored workshop (reported in TRB Circular 247) addressed the above-described subject of compatibility and identified many existing or potential compatibility issues which could conveniently be grouped into four specific categories: airport configurations and facilities; operations at the airport; interactions between the airport and the surrounding community; and the relating of aircraft and airport characteristics to compatibility. Oftentimes these categories are interlinked as exemplified by several of the seven papers reported herein.

The first two papers address the selection of transport aircraft by the air carriers from two different perspectives: the first paper examines a proposed total systems cost process, which includes the cost of airport facilities and operations as well as costs of aircraft and their operations; the second paper describes the present real-world process followed by air carriers which places more importance on those costs pertaining to the aircraft rather than to the total system.

The next three papers pertain to aircraft-compatible airport facilities: a paper describing a greatly improved ramp lighting system recently developed and placed in operation at Chicago; a report concerning an analytical modeling technique to predict the behavior of water runoff from grooved runways; and lastly a companion paper to the modeling study which reports subsequent results of laboratory experiments of water runoff plus associated refinement of the predictive model. The predictive model for water runoff can support not only facility design but also development of improved operational procedures during and after heavy rainfall at airports.

The sixth paper describes an improvement in technology for predicting community noise impact by adding to existing noise footprint prediction techniques the dimensions of a noise/discomfort transfer function and population density distribution. Using a mainframe computer, it proved very useful in trial studies of alternative relocation of runways or flight paths. The computer program is a prime candidate for abridgement to desk-top machines to provide an inexpensive method for meaningful prediction of community noise impact.

The seventh and last paper reports the application of a previously developed compatibility prediction model to a specific, dramatic, real-world situation. The results indicate the predictive model is capable of analyzing complex compatibility issues in an efficient and meaningful manner. While it can be a powerful tool in checking compatibility of new aircraft and airport designs, its future use will depend primarily on the development and maintenance of a comprehensive data base of the several thousand factors which enter into the model.

AIRPORT EFFECTS OF AIRLINER SIZE ON TRANSPORTATION SYSTEM EFFICIENCY

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Abstract

In serving a given passenger flow, the use of larger airliners usually reduces direct operating costs and runway time requirements. A significant disadvantage shown here is that larger airliners spend more time at terminals, thereby reducing aircraft utilization and increasing apron area requirements. That in turn increases airport circulation distances and facility costs. Other disadvantages of larger airliners include reduced service frequency, reduced flexibility in matching capacity to demand, and difficulties in operating within the constraints of existing airports.

This paper quantifies the effect of airliner size on terminal time and apron/gate space requirements, and suggests several ways of reducing those requirements. An optimization of total system costs rather than direct operating costs in the design of airliners is recommended for integrating various elements into an efficient air transportation system.

Introduction

In the air transportation industry it is sometimes taken for granted that larger planes are more efficient, provided that passenger volumes are sufficient to justify their use. In addition to providing lower cost air travel, larger planes are also expected to alleviate the capacity constraints at the busiest air carrier airports. While larger planes do indeed offer some cost and capacity advantages, it does seem that the negative effects of airliner size are underestimated. This paper examines several effects of airliner size on airports and airline operations, identifies remedies for the negative effects, and proposes a method for dealing with such effects in the design optimization of airliners.

Unless otherwise stated, aircraft size will refer to the number of seats per airliner.

To consistently compare airliners of different size it is important to stipulate the proviso "other things being equal." However, other things are rarely equal. For instance, the larger airliners tend to use newer technology, to be designed for longer runways, and to be operated on longer routes. While there are good reasons for these tendencies (as well as many exceptions), the large number of factors hidden in empirical data greatly complicates a purely statistical analysis of airliner size effects. Therefore, technical arguments are used here to supplement the statistical evidence.

The emphasis in this work is on quantifying the effects of airliner size on time spent at terminals and on apron space requirements. These effects have significant implications for the utilization of aircraft, terminal area capacity of airports, circulation distances within airports, and traveller delays. However, several other effects of airliner size are qualitatively reviewed beforehand.

Effects on Direct Operating Costs

In airline cost accounting the direct operating costs (DOC) are the costs directly associated with flying aircraft, namely (1) aircraft depreciation or rental; (2) aircraft maintenance; (3) flight crews; (4) fuel and oil; and (5) insurance. These costs have been analyzed by various researchers including Caves (1), Douglas and Miller(2), Fruhan (3), Gordon (4), Keeler (5), Murphy (6), Speas (7), Straszheim (8), Taneja (9), and Wyckoff and Maister (10). These studies generally indicate that direct operating costs decrease as aircraft size increases, without however focusing on this relationship. Cost data from Taneja (9, p. 50) indicate that the flight operating cost per available ton mile decreases sharply as aircraft size increases for airliners up to approximately 200 seats. Beyond that point, the average flight operating cost decreases quite slowly - slowly enough that the decrease may be attributed to more advancd technology and longer routes flown by the larger airliners in Taneja's data base, rather than to economies of aircraft size.

None of the cost studies cited above have adequately factored out all the effects of speed, range, takeoff and landing performance, seating density, airfreight capabilities, instrumentation, technological state-of-the-art, and management policies. Still, aircraft designers as well as economists have reasons to expect that direct operating costs per available seat mile should follow a relatively shallow U-shaped curve with respect to aircraft size. Initially, the costs decrease with aircraft size for reasons including the following:

(1) The cost of flight crews increases less fast than the airliner seat capacity, although a major component in the pay formula negotiated by the Air Line Pilots Association is based on gross aircraft weight.

(2) The number of components to be manufactured (and hence depreciated in the direct operating costs) and maintained increases less than proportionately with aircraft size. However, to serve a given market with larger airliners, fewer airliners would be built. The larger aircraft would benefit less from production learning curves and would probably cost more to develop.

(3) The aerodynamic drag of aircraft fuselages of given fineness ratio (= length/diameter) increases less than proportionately with the fuselage volume. However, the drag is approximately proportional to the main deck area, which determines seating capacity on most current (i.e., single deck) aircraft types.

As airliners get larger (probably beyond the size of any current types) the costs per seat mile should begin to increase with aircraft size. The main reason offered by aeronautical engineers is the so-called "square-cube" law (11, p. 226). This law states that weight increases with the cube of the linear dimensions, while wing area - and hence lifting ability - increases only with the square of the linear dimensions, other things (notably speed and technical state-of-the-art) being equal. With current technology, the size of aircraft can apparently still be increased without significantly increasing direct operating costs per seat mile. Taneja's (9) data suggest that today's larger airliners operate on the flat bottom of the shallow U-shaped curve.

When larger aircraft are used in a given market, it becomes more difficult to match available capacity to demand. To the extent larger airliners would operate with smaller load factors (i.e., percent seats filled), their relative cost per passenger will be higher than their relative cost per seat. On the other hand, if larger aircraft have lower costs per seat, they may be able to attract more passengers.

Effects On User Costs

To serve a given market with larger aircraft, i.e., to carry a given number of passengers per period between two airports, the frequency of departures must be reduced. The "schedule delay", i.e., the difference between the passenger's desired departure time and the nearest scheduled aircraft departure time is roughly equal to half the headway (i.e., the interval between two successive flights to a given destination) and therefore varies roughly inversely with aircraft size. The value of the schedule delay time represents a cost incurred by users of the air transportation system rather than the airlines. However, since this cost influences the total demand and especially the choice of airline, this user cost significantly influences airline load factors and revenues (1, 2, 3, 9, 12).

Other things being equal, the congestion delay, (i.e., a difference between scheduled and actual arrival time) would be reduced if larger (and thus fewer) aircraft were used at congested airfields.

To the extent larger airliners stay longer at terminals, the delays to passengers (especially on stop-over flights) would be higher.

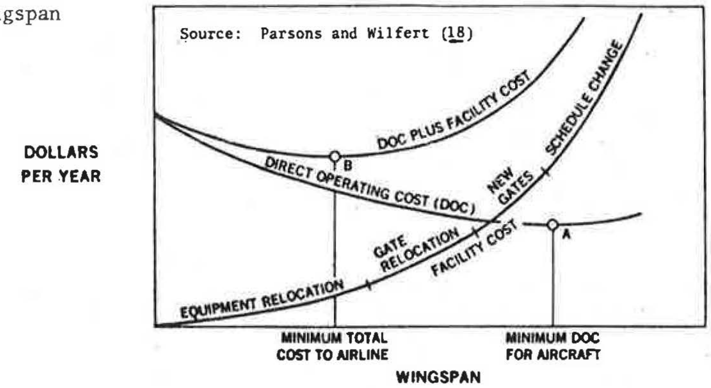
Effects on Airport Facility Requirements

Larger aircraft normally require larger and costlier facilities. They also require fewer facilities of the kind provided in sizeable numbers, such as terminal gates. However, for facilities and equipment provided in small numbers per airport, such as maintenance hangars and spare parts inventories, the costs per available seat are likely to be higher if larger planes are used. For example, if an airline needs just one tractor or hangar for all its traffic at a given airport, the higher cost of a larger tractor or hangar is born by the same traffic if larger airliners are used. The costs of many airport facilities are determined by the characteristics of the largest aircraft to be accommodated, even if that aircraft accounts for a small fraction of operations. For instance, the widths of runways and taxiways, the lateral separations between them, and the turning radii may have to be increased at great expense (assuming additional land can be found at all at some existing airports) if future aircraft substantially exceed the dimensions of current Boeing 747's. Heavier aircraft may also require structural strengthening of overpasses. Fortunately, runway length does not significantly increase with aircraft size, and pavement thickness need not increase if the aircraft weight is well distributed on a proportionally larger number of wheels.

Noise Effects

Other things being equal, the sound intensity emitted by a plane varies with its thrust, and hence, weight. The noise perceived on the ground varies approximately with the logarithm of the sound intensity per plane and of the number of overflights (13). A doubling in either the weight of a given number of planes or in the number of planes would increase the noise exposure forecast (NEF) by about 3 dB. For a given number of passengers carried, the sound

Figure 1. Systems approach to wingspan selection (apron/gate area) (18).



intensity advantage of smaller planes would roughly cancel the overflight repetition advantage of larger planes.

The sound intensity expressed in decibels is:

$$dB = 10 \log_{10} (I/I_o) \qquad (1)$$

where I is the sound intensity in picowats/m^2 and I_o = 1 pw/m^2, which is approximately the weakest audible sound. Thus, a doubling in aircraft weight, and hence I, would increase the noise by approximately 3 dB.

The existing FAR-36 regulations (cited in reference 14, p. 226) allow approximately an additional 4 dB on takeoff and 2 dB on landing (rather than the theoretical 3 dB) for each doubling of aircraft gross weight. Since landing noise is usually more critical due to long approaches at descent angles of approximately 3°, the regulations are slightly tougher for larger airliners and do not fully reflect their advantage in fewer overflights.

Effects On Runway Capacity

The number of passengers served by a given runway can be increased by using larger planes, but not nearly in proportion to aircraft size. Since wake vortex turbulence generated at aircraft wingtips increases directly with aircraft weight, other things being equal, the longitudinal separations between aircraft must be increased considerably behind larger aircraft, especially when these are followed by smaller aircraft (15).

Although the precise effect on runway capacity depends on aircraft mix and on the feasibility of grouping similar aircraft, a rough calculation is illustrative: under present regulations (16, p. 1-18), the minimum IFR separation between successive landings of "large" aircraft (12,500-300,000 lbs. maximum gross weight) is 3 nautical miles. For "heavy" aircraft (over 300,000 lbs.), the corresponding separation is 4 nautical miles. Assuming either group of aircraft has an unrestrictive runway to itself for a time, the runway capacity would be roughly 33 percent greater if "large" rather than "heavy" planes were used. The "heavy" planes would need a seat capacity advantage of more than 33 percent (which they can easily get) to offset their fewer operations.

The wake vortex separation requirements might be reduced considerably (15) if better vortex prediction or detection means were available and/or the wake vortex could be reduced at the source. With better prediction or detection separations could be reduced when atmospheric conditions dissipate the wake vortices quickly. Steeper climb and descent paths and the use of Microwave Landing Systems (17) to guide successive aircraft above the approach or departure slope of preceding aircraft might also reduce separation requirements. The vortex might be reduced at the source by appropriate use of aerodynamic surfaces such as flaps and spoilers (15), by adding winglets at the wingtips, or by increasing wingspan. Since the vortex forces are due to induced drag, which for a given aircraft weight varies inversely with the wingspan, they decrease in inverse proportion to increases in wingspan.

The vortex reduction achievable from wingspan increases can not only increase runway capacity, but also reduce drag - and hence power requirement and fuel consumption. However, increases in wingspan may involve serious difficulties. For a given aircraft weight increases in wingspan result in greater bending moment. For a given wing loading (i.e., weight per wing area) and thickness/chord ratio, the bending moment increases while the thickness (i.e., structural depth) decreases as the wingspan (and aspect ratio - span^2/wing area) is increased. This will result in a larger weight fraction for the wing structure (11, p. 280), along with a higher cost and possibly a lower payload fraction. To the extent larger aircraft require a greater degree of wake vortex alleviation than smaller aircraft, they will incur a cost disadvantage.

In small aircraft, the optimum wingspan tradeoff can be based almost entirely on tradeoffs between structural considerations favoring small aspect ratios and aerodynamic consideration favoring large aspect ratios. In larger airplanes at least four additional factors which are airport related should also be considered: (1) larger wingspans allow reduced approach and departure separations thereby increasing runway capacity; (2) lateral separations between runways and taxiways at some existing airports may constrain permissible wingspans; (3) the dimensions of existing gates and terminal buildings (e.g., the spacing between finger piers) may also restrict wingspans; and (4) larger wingspans for airliners of given size would adversely affect terminal capacity even if reconstruction funding was no problem. Of the above factors (1) and (4) have apparently been neglected. Factors such as (2) and (3) have been considered, as Figure 1 shows. With that figure, Parsons and Wilfert (18) show that the design which minimizes direct operating costs for the aircraft may be far from optimal when facility costs and schedule changes are also taken into account. However, the authors indicate that the figure represents a proposed concept rather than an already applied design approach, and that it is difficult to convince the airlines to go beyond minimum DOC for aircraft as the design requirement.

Figure 2. Effect of aircraft size on through time at gates (19).

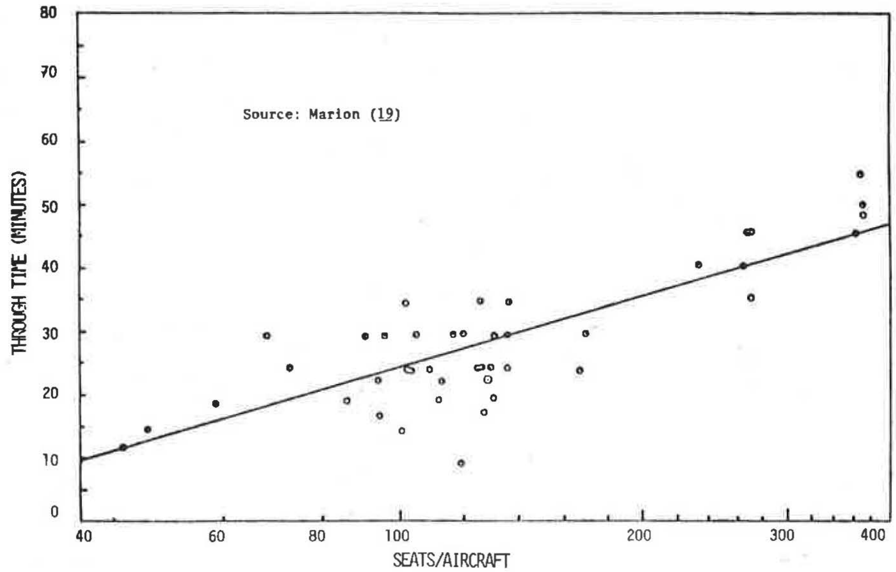
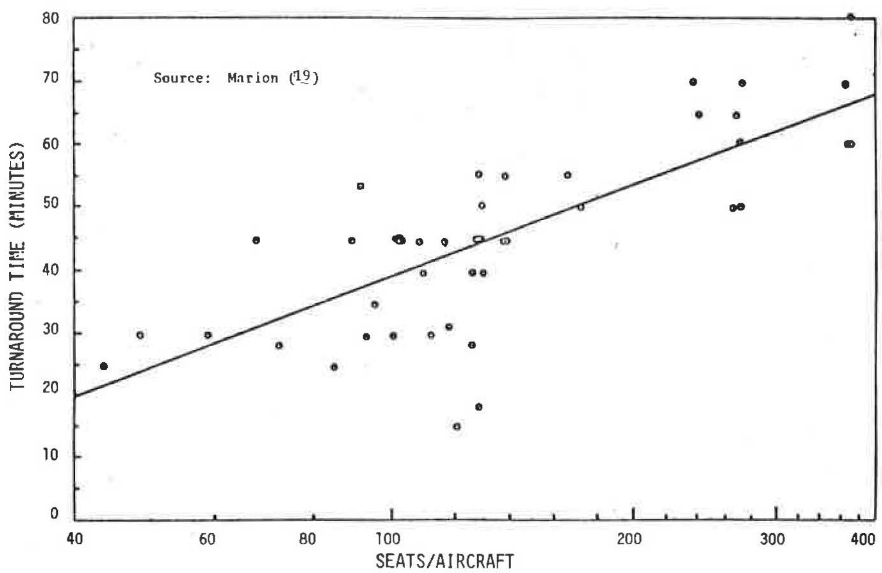


Figure 3. Effect of aircraft size on turnaround time at gates (19).



Effects On Terminal Capacity and Performance

The effects of airliner size on time spent at terminals and on terminal capacity will be addressed more thoroughly than the effects mentioned in previous sections, since published material on them is practically unavailable. The results presented here suggest that these effects are quite significant and should not be neglected.

Gate Time The effect of airliner size upon gate time, i.e., the time required for servicing, unloading, and loading airliners at the terminal, was the subject of a 1980 study directed by the author. In that study Marion (19) identified various factors affecting gate time, and through statistical analysis related gate time to airliner size. Although for competitive reasons airlines are rather secretive about gate time data, 14 airlines (including most major airlines and most of the airlines contacted) were willing to provide gate times for their main aircraft types. The gate times are plotted in Figures 2 and 3 for "through" operations and "turn around" operations, respectively. "Through" or "stopover" times are considerably shorter than turnaround times because only a fraction of the passengers and baggage are unloaded or loaded and less servicing (e.g. cleaning, fueling, provisioning) is usually necessary. Each data point in Figures 2 and 3 represents the average gate time for one airliner type operated by one airline. The statistical analysis indicated that the following equations provided the best fit to the data on through and turnaround times:

$$T_t = -49.95 + 37.21 \log S, \quad r^2 = .669 \qquad (2)$$

$$T_a = -57.63 + 48.29 \log S, \quad r^2 = .573 \qquad (3)$$

where: T_t = through time in minutes
T_a = turnaround time in minutes
S = aircraft size expressed in seats/aircraft
r^2 = coefficient of determination.

There is considerable scatter in the data shown in Figures 2 and 3. The standard deviation is 5.84 minutes for the estimated through time T_t and 9.01 minutes for the estimated turnaround time T_a. Such scatter indicates that airliner size is not the only factor determining gate time. Among the many other contributing factors are actual volumes of passengers, baggage and cargo handled (as opposed to aircraft capacity), availability of manpower and equipment, terminal configuration, special handling requirements (e.g., for wheelchair passengers or hazardous cargo), the nature and extent of serviceing (e.g., maintenance checks and cabin cleaning) specified by airline policies, and weather conditions (de-icing being especially time consuming). While the above factors may all be important, Figure 2 and 3 show a strong relation between gate time and aircraft size. By its definition, the coefficient of determination r^2 indicates what fraction of the variation in the dependent variable (gate time) is attributable to the independent variable (seats per aircraft). The above analysis indicates that about 67 percent of the variation in through time and 57 percent of the variation in turnaround time may be attributed to the number of seats per plane. Although some hidden variables such as length of flight and aircraft access configuration (i.e., doors and aisles) may be lumped into the aircraft size variable, the effect of aircraft size seems to be quite significant.

Using Equation 2, we can see that through time roughly doubles from 23.47 to 46.87 minutes as aircraft size increases from 94 to 400 seats. Equation 3 indicates turnaround time doubles from 34 to 68 minutes as aircraft size increases from 79 to 400 seats.

These results are obtained from actual operations rather than theoretical possibilities. If substantial improvements in gate time are possible, they would apply to small as well as larger airliners.

The increased gate time for larger airliners has some important practical implications. Other things being equal, the utilization of airliners decreases as their gate time increases. For example, on a New York City-Detroit shuttle (482 miles each way) flight time at typical subsonic jet speeds would be fairly close to 68 minutes. From Equation 3 the estimated turnaround time is 68 minutes for a 400 seat airliner and 34 minutes for a 79 seat airliner, resulting in 272 minutes per round trip cycle for the 400 seater and 204 minutes per cycle for the 79 seater, i.e., a 4 to 3 advantage in round trips per period for smaller planes. This example may be atypical (and the larger plane may still have lower direct operating costs in spite of its lower utilization), but it does illustrate one reason why the airlines should (and generally do) avoid using large planes on relatively short routes. The actual utilization (in flight hours per day) of large airliners tends to be relatively higher due to the justifiable tendency of using them on longer routes, with fewer stops, where service frequency is less critical because the schedule delay is smaller in relation to the total trip time.

The higher gate time of larger airliners, also has important implications for terminal area capacity and costs, as discussed below.

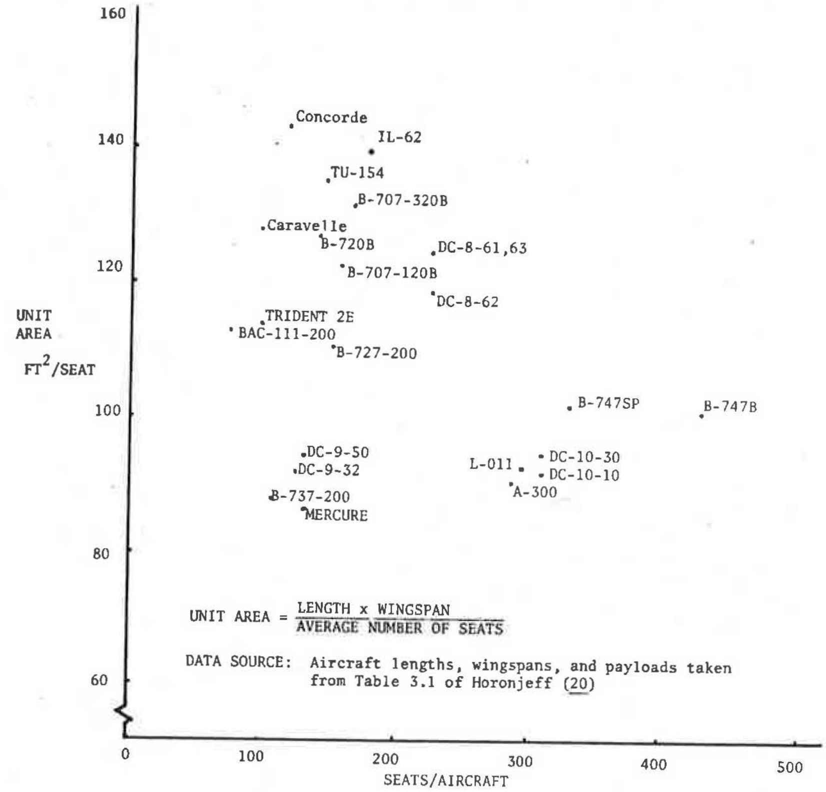
Apron/Gate Area Requirements The apron is the aircraft parking area in front of the airport terminal buildings. At many airports the available apron space is boxed in by runways and/or access roads, or is limited for other reasons. Unlike landside facilities, this space cannot realistically be expanded vertically to several levels. At some airports the available apron space may become the critical capacity bottleneck if runway capacity can be significantly improved by the new Microwave Landing Systems. In such cases the opportunity cost of apron space, i.e., the cost of not having more of it available, can be much higher than the nominal cost of land and pavement. It should also be noted that even if apron space were cheap and unlimited, there are significant advantages in having a compact terminal area. These advantages include the cost of airport buildings, and circulation distances within airports - especially among connecting flights.

The unit area, i.e., the apron space required per seat does not vary significantly with airliner size, other things being equal. The "other things" include design, speed and range, runway length required, seating density, and technological state-of-the-art. Figure 4, whose data points are computed from Table 3.1 of Horonjeff (20), shows unit areas (in square feet of apron per seat) ranging from 87 for short range twinjets to 144 for Concorde. The scatter of the data points indicates that unit area does not vary systematically with seat capacity. For aircraft of similar technology and performance but different seat capacity such as the B-747B and the B-747SP or the Trident 2E and the B-727-200, the unit areas are very similar. There is also little difference between the short range twin-jets (DC-9, B-737, Mercure) and the medium range wide-body jets (DC-10, L-1011, A-300). Although aircraft in the latter group have longer range, they also benefit from more advanced technology and their design may have been more constrained by gate dimensions.

A chain of aeronautical engineering arguments can also be used to explain why unit area does not vary significantly with aircraft size:

1. Assume "other things being equal", i.e., the same performance requirements (e.g., speed, range, runway length), technological state-of-the-art, design maturity (or stretching"), and general configuration apply regardless of the number of seats per aircraft.
2. The gross weight is then roughly proportional to seat capacity.
3. The wing area is proportional to gross weight and hence seat capacity, i.e., wing loading is independent of seat capacity.
4. At a given aspect ratio, the wingspan varies with the square root of wing area, and hence of seat capacity.
5. Aircraft length also varies roughly with the square root of the gross weight and seat capacity. This argument is based either on the moment arm required for stability and control or on the need to provide sufficient cabin floor area in a fuselage of given fineness (i.e., length to diameter ratio). The cabin floor area argument changes if multi-level passenger cabins are used, but the control requirements still apply. Even with automatic active controls an adequate moment arm is required for maneuvering, takeoff rotation and landing flareout (11, p. 307).

Figure 4. Apron area occupied by various aircraft.



6. Since both wingspan and length vary with the square root of passenger capacity, the area taken up by an aircraft varies in proportion to its seat capacity.

7. For some movements and parking configurations only the square of the wingspan, which is proportional to seat capacity, determines apron area required per aircraft. In such cases step 5 is superfluous.

8. If clearances (e.g., between adjoining aircraft wingtips) are either small compared to aircraft linear dimensions or a constant percentage of those dimensions, they will not significantly affect the invariance of unit area with airliner size.

The major implications of invariant unit area are:

1. Passenger handling capacity per given apron/gate area is lower for larger aircraft since they occupy a proportionally larger area for a longer time. Alternatively, large airliners require proportionally larger gate areas. While the passenger capacity per gate increases, the passenger capacity per gate area decreases as larger airliners are used. It should be noted that this effect is based on data for current airliners rather than hypothetical airliners of the future.

2. Since more apron/gate area is required for a given passenger capacity, the cost of land and pavement, the internal circulation distances for passengers and service vehicles (e.g., for baggage and cargo transfers), the costs of more extended terminal facilities, and possibly the taxiing distances for aircraft, are increased when larger aircraft are used. Algebraically, the relations may be expressed with the following simple equations:

$$u = \ell b/s \quad (4)$$

$$q = \frac{\sigma}{KuT} \quad (5)$$

$$A = \frac{v}{q} = \frac{vkuT}{\sigma} \quad (6)$$

where:

u = unit apron area in ft^2/seat

b = wingspan in feet

ℓ = aircraft length in feet

s = aircraft seat capacity

q = unit apron capacity in pass/ft^2 per minute

σ = seat turnover factor = number of arriving and departing passengers per seat

k = clearance factor = actual area used per aircraft/ℓb

T = gate time per aircraft in minutes = weighted average of turnaround and through times

A = total apron area required in $ft.^2$

v = volume in passengers/minute (includes arrivals and departures)

Equation 6 shows that the required apron area A varies directly with the gate time T. In turn T varies with the aircraft seat capacity S according to Equations 2 and 3. Other things (including passenger volume) being equal, the required apron area A would similarly vary with S. Internal airport circulation distances, which should vary approximately with the linear dimensions of the apron area (20), would vary approximately with $T^{1/2}$. Recalling a previous example, for a given passenger volume, if turnaround operations with 400 seat planes completely replaced turnaround operations with 79 seat planes, T_a would double from 34 to 68 minutes. Assuming v = 50 pass/min, k - 1.2, u = 100 $ft.^2$, and σ = 1.0 (i.e., 50 percent load factor in each direction), the unit apron capacity q would decrease from 2.45 x 10^{-4} passengers/$ft.^2$ minute, the required apron area A would double from 204,000 $ft.^2$ to408,000 $ft.^2$ and the internal circulation distances would increase by a factor of $2^{1/2}$, i.e., by roughly 41 percent. The cost of connecting structures would also increase considerably as the apron area doubled.

Potential Solutions

Although dimensional constraints at airports are more likely to affect (aircraft designers might say "compromise") large airliners, reasons have been given for reducing the dimensions of most airliners. Several approaches might be taken.

For a given payload, the aircraft length is more difficult to reduce than the wingspan. Still, by increasing the size of the control surfaces, or with improved electronic active controls, the moment arm between the control surfaces and the aircraft center of gravity might be shortened. For a given payload, a shorter fuselage would have to be fatter, especially in the case of smaller planes where only one cabin level is practical. Such fatter fuselages would incur some drag penalties along with some structural weight and loading flexibility advantages.

The wingspan is usually more critical than the length (e.g., in separations between parallel runways and taxiways) and also somewhat easier to vary. For a given wing loading, a smaller wingspan and aspect ratio result in higher induced drag (and therefore, higher fuel consumption and wake turbulence) but smaller structural weights for aircraft and dimensional requirements for airports. Concerns with fuel consumption have tended to increase wingspans in recent designs.

To satisfy the conflicting requirements, aircraft designers might consider variable geometry solutions such as swing wings, scissor wings, and telescoping wings. Though it seems doubtful that the complexity, weight, and cost of such solutions would be justifiable on subsonic airliners in the near future, it is conceivable that the aerodynamics at various speeds and altitudes would improve enough to actually reduce weight and DOC, as well as alleviate dimensional problems at airports.

Another solution might be to fold the wings when taxiing and parking at gates. The amount of airport space saved, but also the aircraft cost and weight, would increase as the wingfold hinges were moved nearer to the fuselage.

The wingspan can also be reduced by providng winglets at the wingtips. Such winglets, which reduce induced drag and hence the motivation for large spans, are already being used on some business jets.

The required apron area might also be reduced if necessary, by allowing aircraft wings to move above or under other aircraft wings on the ground. This could be achieved by bringing smaller (and lower) planes in-between larger ones next to terminal buildings or by providing planes with variable height landing gear. Such landing gear might be used to raise a plane above or lower it below adjoining planes, or perhaps even to slant it sideways (i.e., bank it) in between similarly slanted planes. Variable height landing gear would increase aircraft weight, but it may also be beneficial in loading and unloading operations, and in giving aircraft the proper takeoff attitude.

Apron/gate area capacity may be increased either by reducing the unit area occupied by aircraft, or by increasing the utilization of that area. While better scheduling of aircraft and tractors may somewhat improve apron utilization, the main improvements should be sought in gate time reductions. Such reductions may be achieved through aircraft design changes (e.g., more and/or wider aisles and doors), improved gate facilities and equipment, and increases in labor.

Since these are all costly, thorough economic justification would be required for their implementation. In fact, any suggested approach should be critically evaluated and rejected if its costs outweigh its benefits. Still, there are numerous examples in aviation history of solutions which seemed unreasonably heavy, costly, or even dangerous before they were successfully applied to satisfy challenging design requirements.

It should also be noted that ongoing technological advances could help reduce aircraft dimensions. Improved material and structural design reduce structural weight, while reductions in fuel consumption reduce gross weight. These improvements are synergistic: reduced weight reduces fuel consumption, and reduced fuel consumption reduces weight. Since wing area varies with aircraft weight, improvements in the payload to weight ratios could translate into wingspan reductions. However, recent airliner designs have increased wingspans to reduce fuel consumption.

System Optimization

Designers of airliners, following the wishes of their airline customers, have generally concentrated on minimizing the direct operating costs of their planes. The effects of aircraft characteristics on airport costs have not been their primary concern, although increasing attention has been devoted recently to gate operations. Aircraft designers may have implicitly assumed that the costs of compromising aircraft are much greater than the costs of providing airports for optimal aircraft. The competitive airlines for which they design planes cannot afford to do much about costs incurred by public agencies, competing users of airports, or airport neighbors, unless regulations require all competitors to do so. Airliner design has been influenced by airport constraints, e.g., on runway length, pavement thickness, and noise levels, but airport costs have apparently not yet been included in the objective function for airliner design, notwithstanding some forward-thinking proposals by Parsons and Wilfert (18).

To optimize the total air transportation system and insure the compatibility of aircraft and airports, it seems desirable that designers of airliners should optimize a total system cost (TSC) function rather than a direct operating cost (DOC) function. Even the Total Operating Cost (= Direct Operating Cost + Indirect Operating Cost) used in airline accounting may not be comprehensive enough. Ideally, the TSC should include such elements as the value of the passengers' time, airport access costs, and noise impacts. Such costs would be important in evaluating short take-off and landing (STOL) designs, or even in determining whether an aircraft should be designed to operate at small airports such as N.Y. - LaGuardia, Chicago-Midway, and Washington-National.

If those costs seem too broad to handle, designers should at least consider a TSC function that includes the true "opportunity" costs of airport capacity. In addition to the direct operating costs (DOC) and those indirect operating costs (IOC) affected by aircraft design (e.g., baggage and cargo handling costs), this function should explicitly include an airfield cost element and an apron/gate cost element. They should be based on the estimated marginal costs of using particular facilities during particular periods. For example, an aircraft considerably larger than today's B747's might restrict operations on adjacent runways and taxiways for periods longer than its runway occupancy time. The time those facilities are unavailable to other users should then be charged to this aircraft.

Since the above costs would vary greatly with the geometric characteristics of various airports and with volume/capacity ratios at various times of day, the designers would need to work with either an extensive data base or with some aggregate cost functions that would relate airport costs to aircraft design characteristics. For instance, the apron cost function might look as follows:

$$C_a = \ell bk \sum_f \sum_p c_{fp} T_{fp} \tag{7}$$

where:

C_a = apron cost in \$/aircraft year

ℓ = aircraft length in feet

b = wingspan in feet

k = clearance factor $\cong 1.2$

f = facility index identifying an airport or part of an airport

p = period index identifying the time of day (or week, or season) when a facility is used

c_{fp} = cost in \$/ft.^{2} per hour of using facility f during period p

T_{fp} = time of usage of facility f during period p in hours/aircraft year

The time of usage T_{fp} used in Equation 7 would be the product of the number of flights per year and the gate time:

$$T_{fp} = T_t N_{tfp} + T_a N_{afp} \tag{8}$$

where:

T_t gate time for through flights in hours

T_a = gate time for turnaround flights in hours

N_{tfp} = number of through flights per year at facility f during period p

N_{afp} = number of turnaround flights at facility f during period p.

The gate times T_t and T_a may be obtained from Equations 2 and 3 for existing airliners and operating procedures. Future improvements may warrant revised equations for T_a and T_t.

While aggregate cost functions such as Equation 7 may simplify the highly iterative process of aircraft design, a considerable data base on airport characteristics, and on airline operation costs at the various airports would still be necessary to develop and apply such functions.

It should be noted that the optimization of total system costs outlined above would not be particularly relevant to airlines unless the marginal costs were actually paid by airlines. Under present arrangements, landing fees which are based on aircraft gross weights rather than occupancy times and congestion levels cannot reflect the marginal costs of using congested airfields. The use of marginal cost pricing may be disadvantageous for extra large aircraft at some airports, but its main effect would probably be to discourage small aircraft from using air carrier airports (or runways) during busy periods. To the extent gate rental fees are based on occupancy times they are more closely related to marginal costs. They could be related even more closely if the fees varied with congestion levels. The eventual effect of aircraft design on gate rental fees may already constitute an incentive to airlines to consider aircraft-airport tradeoffs.

The suggestions expressed above place additional burdens on aircraft designers. They are not intended to relieve airport authorities of their responsibilities for providing an efficient and integrated air transportation system. Airport planners and managers usually have the motivation to accommodate more numerous and efficient airliners and to improve service at their facilities. Although the aircraft manufacturers are in a key position to influence the overall efficiency of the system, their designs must satisfy their airline customers. Competitive airlines cannot afford to accept design characteristics which increase their operating costs for the sake of reducing total system costs unless 1) such characteristics are mandated by government as is the case for noise standards; 2) such characteristics are required by some key airports (e.g., the A-300 landing gear had to be modified for acceptance at La Guardia Airport); or 3) the airport fees paid by airlines reflect marginal costs to the system.

Conclusions

The arguments presented above are not intended to advocate the use of small airliners, but rather to identify, partly quantify, and suggest remedies for some disadvantages of larger airliners which seem to be neglected.

In serving a given passenger flow, larger airliners offer advantages in direct operating cost and in the passenger capacity of runways. Their main disadvantages are reduced service frequency and, as shown in Equations 2 and 3, increased terminal time. Increased terminal time decreases aircraft utilization and, since the apron area required per seat does not vary significantly with aircraft size, also increases the terminal area required per passenger served. That in turn increases the internal circulation distance and facility costs at airports. Other disadvantages of larger aircraft include higher development costs, smaller production runs, reduced flexibility in matching capacity to demand, and possible difficulties in operating within the geometric and structural constraints of existing airports.

Some negative consequences of aircraft size can be alleviated by technological advances, somewhat more complex designs, and more manpower and equipment at terminals. The tradeoffs required to achieve an efficient and integrated air transportation system should be made by optimizing total system costs rather than direct operating costs when new airliners are designed.

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