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VALIDATION OF MAXIMUM AIRPORT THROUGHPUT LEVELS ESTIMATED BY THE DELCAP SIMULATION MODEL

Judith F. Gilsinn

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16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

This report documents exercises of the DELCAP airport terminal area simulation model performed to validate the maximum throughput calculations of that model. DELCAP was run for five different runway configurations, with three or four appropriate operating policies chosen for each, and for three different mixes of aircraft types. Throughput estimates from DELCAP are found to be in general agreement with current values provided by the FAA. One specific instance of greater discrepancy is identified, and a remedy for it is proposed. Changes made in DELCAP since its original documentation in 1971 are described in an appendix.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

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TABLE OF CONTENTS

LIST OF TABLES

TABLE OF CONTENTS (CONTINUED)

LIST OF FIGURES

1. INTRODUCTION

Once a mathematical model has reached operational status, there is a natural temptation to put it directly to practical use, skipping over any substantial effort to verify that the model does in fact do what it was designed to do. Such an omission, however, courts disaster, since a model which has not been exercised on a variety of data (and had its outputs compared with what is actually observed in the situation being modeled) may contain unsuspected anomalies likely to exhibit themselves at embarassing moments or (even worse) to remain undetected. To guard responsibly against this, it is necessary to subject the model to a pre-use validation and preliminary sensitivity analysis.

Validation involves two types of analysis. The first is an independent examination of the design and construction of the model--to detect weaknesses, to anticipate problem areas, and to insure an independent assessment of the appropriateness of the structure and methods used. A second element of validity checking is the comparison of model outputs with those actually observed in specific instances of the type of situation being modeled. Comparison of model performance with that of other models which are well-based and accepted, for cases to which both apply, could also be part of this type of analysis. Absolute assurance of validity for all possible future uses is,of course, impossible. Replication of reality for a few test cases can only insure that in these particular examples, the model performs as it should, but if the test cases were chosen carefully to be representative of the spectrum of situations to which the model is expected to be applied, then increased confidence in model validity can be obtained.

Beyond the basic validity testing described above, some preliminary sensitivity analyses should be conducted--to identify those parameters having most critical (most sensitive) effect on model outputs, and to ascertain the degree to which model outputs can be expected to vary with input variations. Such sensitivity analyses should also help to determine the limits beyond which application of the model is inappropriate.

The present report describes validation exercises and preliminary sensitivity analyses of the DELCAP airport simulation model, documented in FAA Report Number FAA-RD 71-9.* Modifications to the DELCAP model have been made subsequent to the publication of that document in order to accommodate separation requirements for heavy aircraft not in effect when DELCAP was designed, to provide additional outputs requested by FAA's Air

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*Judith Gilsinn, E. H. Short, W. A. Steele and D. Klavan, A Simulation Model for Estimating Airport Terminal Area Throughputs and Delays, NBS Report 10592, May 1971.

Traffic Service for the current study, and to allow more flexible sequencing of operations on runways handling both landings and takeoffs. These modifications are detailed in an Appendix to this report.

1.1 Description of DELCAP

DELCAP is a simulation model, written in the SIMSCRIPT computer language, of the airport terminal area including terminal airside operations and those ground operations occurring on the runway surface. Its output consists of throughput and delay figures. Input includes traffic levels (or the explicit schedules of traffic, or both), the mix and characteristics of aircraft types, the separation rules which apply, the airport runway configuration and runway operating policies.

Figure 1.1 displays the terminal area as seen by the DELCAP model. The aircraft denoted by capital letters are landings; those designated by lower case letters are takeoffs. The landing and takeoff streams are lettered in the order of their entrance to the model. (The particular configuration and operating policy shown--a pair of intersecting runways, one handling only takeoffs, the other only landings--is illustrative and should not be taken as a model restriction. Runway configuration is a model input; as will be shown by the exercises reported in Chapter 2 a wide variety of such configurations can be handled by DELCAP.)

It is convenient to describe DELCAP's treatment of landing and takeoff streams separately, since DELCAP is an event-oriented model (time is incremented to the next "critical event," rather than stepped along at preset intervals) and each critical event in an aircraft's path anticipates the next one along that path. Landings enter the simulation at handoff to tower approach control (E in Figure 1.1). The next critical point along a landing path is the outer marker. DELCAP requires that at least a preset minimum time interval ensue between handoff and the landing's passage of the outer marker. However, the presence of other aircraft in front of E in the landing stream may necessitate that it be placed in a holding pattern or that it fly a longer path to the outer marker, either of which would require extra time. DELCAP does not model the actual route flown by E, but this extra time requirement is imposed by the modeling device of "trying up" the outer marker, i.e., prohibiting E from passing it, until all those in front have done so.

Once the aircraft in front of the current one (say D in the figure) has passed the outer marker, its final approach can be scheduled.

FIGURE 1.1

<u>The Terminal Area as Seen by DELCAP</u>

<u>TAKEOFFS</u>

d. at gate
c. taxi from gate to runway
b. start roll
a. lift off

<u>LANDINGS</u>

E. handed off to tower
D. fly from handoff to outer marker
C. cross the outer marker
B. fly final approach
A. land

D must remain separated from C by the required amount (presently 3 miles if C is not a heavy aircraft, 4 miles if both C and D are heavies and 5 miles if C is a heavy but D is not) along the whole final approach path. DELCAP employs the idealization of constant final approach speeds (dependent on aircraft type), and so the actual separation required between C and D when D crosses the outer marker is either (if C is faster) the minimum required spacing between these aircraft, or (if D is faster) a spacing such that when C touches down D will be at the required minimum separation distance from the end of the runway.* A landing leaves the simulation when it turns off the runway.

Takeoffs enter the simulation about 15 minutes before scheduled departure time. A minimum taxi time between gate and runway is specified. Since in Figure 1.1, landing A has passed the runway intersection, takeoff b can be cleared to start its roll, if takeoff a has sufficient separation from takeoff b; this presently is 2 minutes after a lifts off if a is a heavy and b is not, and is a shorter, constant time interval--approximated as 30 seconds after liftoff--for all other aircraft-type combinations.

Figure 1.2 is a flowchart of the simulation. The bottom box, "choose next operation," represents the implementation of the runway operating policy which determines the sequence of landings and takeoffs on each runway. The two boxes referring to "maintain separation" are implemented in the model by "tying up" critical points in the landing and takeoff paths: the point at which a takeoff starts its roll, the outer marker, and the point at which a landing touches down. A landing or takeoff can be scheduled to take place only at a time such that any tieup affecting its progress will no longer be in force when it reaches the affected critical point.

The DELCAP model has been designed to provide output of two quantities, namely, throughput (the number of operations handled by the facility per time period) and delay. Application of DELCAP is envisaged under two different scenarios. The first is one in which a realistic demand level is stipulated and DELCAP output yields resulting delays and throughputs. In the second scenario, DELCAP is run with unrealistically high demand levels to estimate the airport's maximum throughput (capacity).

It is this second scenario under which the validity of DELCAP is investigated here. Testing has been limited to this case because

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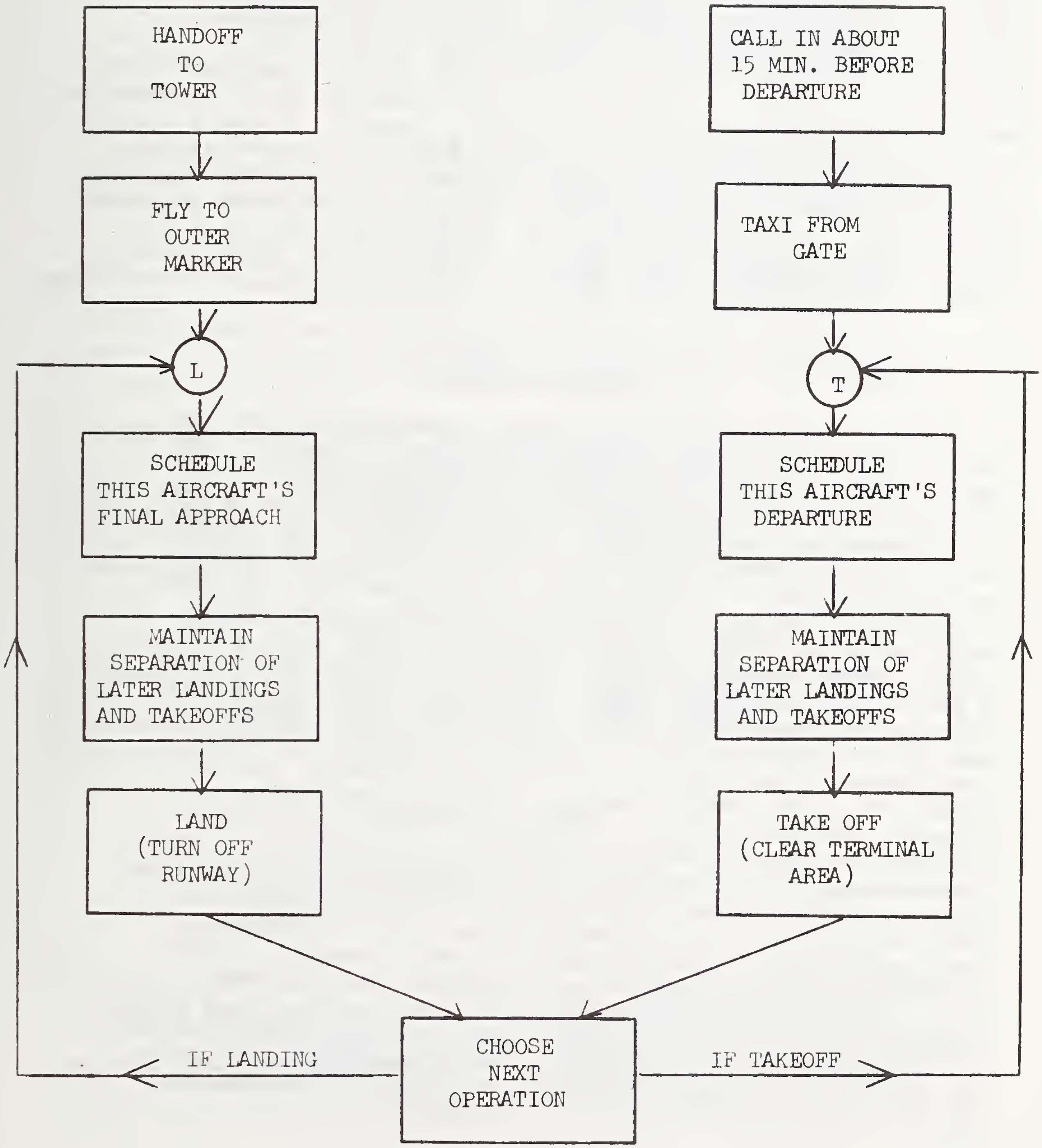
*Of course B cannot land as long as A is on the runway surface. That is, in addition to the airborne separation requirements, runway occupancy time also can affect the actual separation between B and A. DELCAP includes the "tying up" effects of runway occupancy, though in practice, it is usually the airborne separation which is critical.

FIGURE 1.2

Flowchart of the DELCAP Simulation



the main application which this validation effort supports operates in the second scenario. That application is the computation of performance standards, throughputs which are achievable under heavy traffic conditions, for several of the nation's busiest airports operating under a variety of possible configurations and operating policies. A second reason for validating DELCAP only in its "capacity" mode is that the concept of "delay" is somewhat vague and as a result delay figures are calculated differently (even within the FAA) by different people in different places. The definition used by DELCAP is the difference between (1) the actual time between an aircraft's entrance into DELCAP and its landing or takeoff, and (2) the minimum time needed to execute that procedure were there no other aircraft in the system. This definition, while both intuitively reasonable and clear, does not agree with many FAA definitions of delay, since for instance an aircraft's flying a stretched-out path from the feeder fix to the outer marker would not contribute to FAA-computed delay but would be considered delay by DELCAP. Lacking comparable figures on observed delays, the main procedure for checking DELCAP's delay outputs will have to be an independent detailed check of model logic and delay computations. Such an effort is in progress; meanwhile, we look forward to collection of delay data which are comparable.

1.2. Validating DELCAP

The validation exercises employed to test DELCAP under the second scenario above are described in detail in Chapter 2, and their results are compared with values obtained from FAA's Air Traffic Service in Chapter 3. These tests were designed in consultation with R. Scott of FAA's System Research and Development Service and R. Woods and R. Tobiason of the Air Traffic Service, to cover that set of configurations most representative of those encountered at major U.S. terminals, including a single runway, two intersecting runway configurations (differing in the placement of the intersection), a pair of close parallel runways, and a pair of close parallels with a third runway crossing the pair. Wide parallels were not included since they can be modeled as two separate single runways. A variety of operating policies were chosen to approximate those used under different traffic situations: when landings balance takeoffs, when landings predominate, and when takeoffs predominate. This diversity also allows comparison of results to evaluate the sensitivity of DELCAP throughputs to operating policy. The exercises included different mixes of aircraft types, focusing primarily on the fraction of heavy aircraft in the mix since different, larger separations are required behind heavies because of wake turbulence. Other model inputs (such as aircraft characteristics or the length of the final approach path) could also have been varied, but preliminary tests have led us to believe that the three factors mentioned--configuration, operating policy, and aircraft-type mix--are the ones most critically affecting differences in throughput at major U.S. terminals.

2. VALIDATION RUNS

2.1 General Description

This chapter documents runs of the DELCAP model designed to test the validity of its throughput calculations under a variety of conditions. The characteristics attributed during these runs to each of three aircraft types--heavy aircraft (over 300,000 lbs. gross weight), small aircraft (most single- and two-engine craft), and medium and larger craft (larger piston aircraft and most jets)--are described in Table 2.1. These values were obtained from data collected by the Air Traffic Service at ORD.

Five different runway configurations, thought to be representative of those most often encountered and described in greater detail below, were investigated: a single runway, two runways intersecting so as to form a V, two runways intersecting to form an X, a set of close parallels (3000 to 4300 feet apart), and a set of close parallels with a crossing runway. As noted above, configurations involving wide parallels are not included in this analysis since the DELCAP model treats wide parallels as two completely separate runways, and as a result, the maximum throughput of a pair of wide parallels is just the sum of those available from them independently.

For each configuration, operating policies (displayed in Table 2.3) were chosen as most reasonable for each of three arrival/departure mixes: arrivals balancing departures, departures dominant, and arrivals dominant. Each configuration and operating policy was investigated for three aircraft-type mixes, identified by the percentage of heavy aircraft in the mix and described more fully in Table 2.2.

For each configuration, operating policy and aircraft-type mix, the model was run to simulate 20 hours of traffic. The average hourly throughputs (averaged over the sample of 20 hours) of landings, takeoffs and all operations were recorded for each runway and totaled for all runways to permit comparisons among policies, type mixes and configurations.

2.2 Validation Output

2.2.1 SINGLE RUNWAY

The single runway case has been studied extensively,* and admits

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*See for example FAA Report RD-69-47, Analysis of a Capacity Concept for Runway and Final-Approach Path Airspace, NBS Report 10111, November 1969. and Continued Analysis of a Capacity Concept for Runway and Final-Approach Path Airspace, NBS Report 10589, April 1971. Similar formulas to those appearing below appear in these publications, but are derived here again for completeness.

TABLE 2.1

Aircraft Characteristics for Validation Runs

Type Number	Type Description	Speeds (Knots) Landing	Liftoff	Runway Occupancy (Sec) Landing	Takeoff
1	Heavy A/C	124	120	55	33
2	Small A/C	119	90	40	27
3	Category III's (Larger A/C)	120	120	50	32

TABLE 2.2

Three Aircraft-Type Mixes Used

Mix I - 5% Heavies

Type	% in Mix
1	5%
2	17%
3	78%

Mix II - 15% Heavies

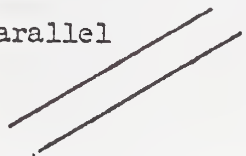
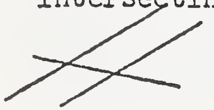
Type	% in Mix
1	15%
2	15%
3	70%

Mix III - 50% Heavies

Type	% in Mix
1	50%
2	9%
3	41%

TABLE 2.3

Configurations and Operating Policies for Validation Runs

Arrival/ Departure Mix	Arrivals = Departures			Departures Predominate			Arrivals Predominate		
% Heavies	5%	15%	50%	5%	15%	50%	5%	15%	50%
Configuration									
Single runway 	Alternate			Two departures between each pair of arrivals			Two arrivals between each pair of departures		
Intersecting 	1. Arrivals on one, Departures on the other 2. Alternate on both			Alternate on one, Departures on the other			Alternate on one, Arrivals on the other		
Intersecting 	1. Arrivals on one, Departures on the other 2. Alternate on both			Alternate on one, Departures on the other			Alternate on one, Arrivals on the other		
Parallel 	Alternate on both			Arrivals on one, Departures on the other			Alternate on one, Arrivals on the other		
Parallel + Intersecting 	Arrivals on one parallel, Departures on the other, Alternate on crossing runway			Departures on one parallel, Alternate on the other two runways			Arrivals on one parallel, Alternate on the other two runways		

analytical expressions for capacity. Two such expressions, one for a runway handling takeoffs only and the other for the same runway handling landings only, are derived below. As will be seen, DELCAP outputs for these single-runway situations conform closely (as they should) to these theoretical formulas.

To calculate the expected value of the maximum throughput for a single runway handling takeoffs only, under the assumption of a continuous stream of departures in which heavy aircraft appear randomly and constitute a known fraction of all takeoffs, let

N = number of takeoffs per hour,
p = fraction of takeoffs which are heavies,
r = runway occupancy time (hrs.) for heavies,
Δ = average time (hrs.) between takeoffs for non-heavies
δ = average time (hrs.) between takeoff of two heavies (Note that separation rules require a non-heavy to wait 2 minutes after a preceding heavy liftoff before starting its roll.)

Then it follows that:

1. The time between takeoff of a heavy and that of a following non-heavy is $r' = r + 2/60$, the time between takeoffs of heavies is δ, and the time between takeoff of non-heavies is Δ.
2. A fraction p of aircraft following a heavy are heavies; (1 - p) are non-heavies.
3. The expected number of hourly takeoffs by heavies is pN; for non-heavies it is (1-p)N.

Thus the following equation (between numbers of hours) holds:

$$pN[p\delta + (1-p)(r')] + (1-p)N\Delta=1$$

or

$$N = 1/[p^2\delta+p(1-p)r' + (1-p)\Delta]$$

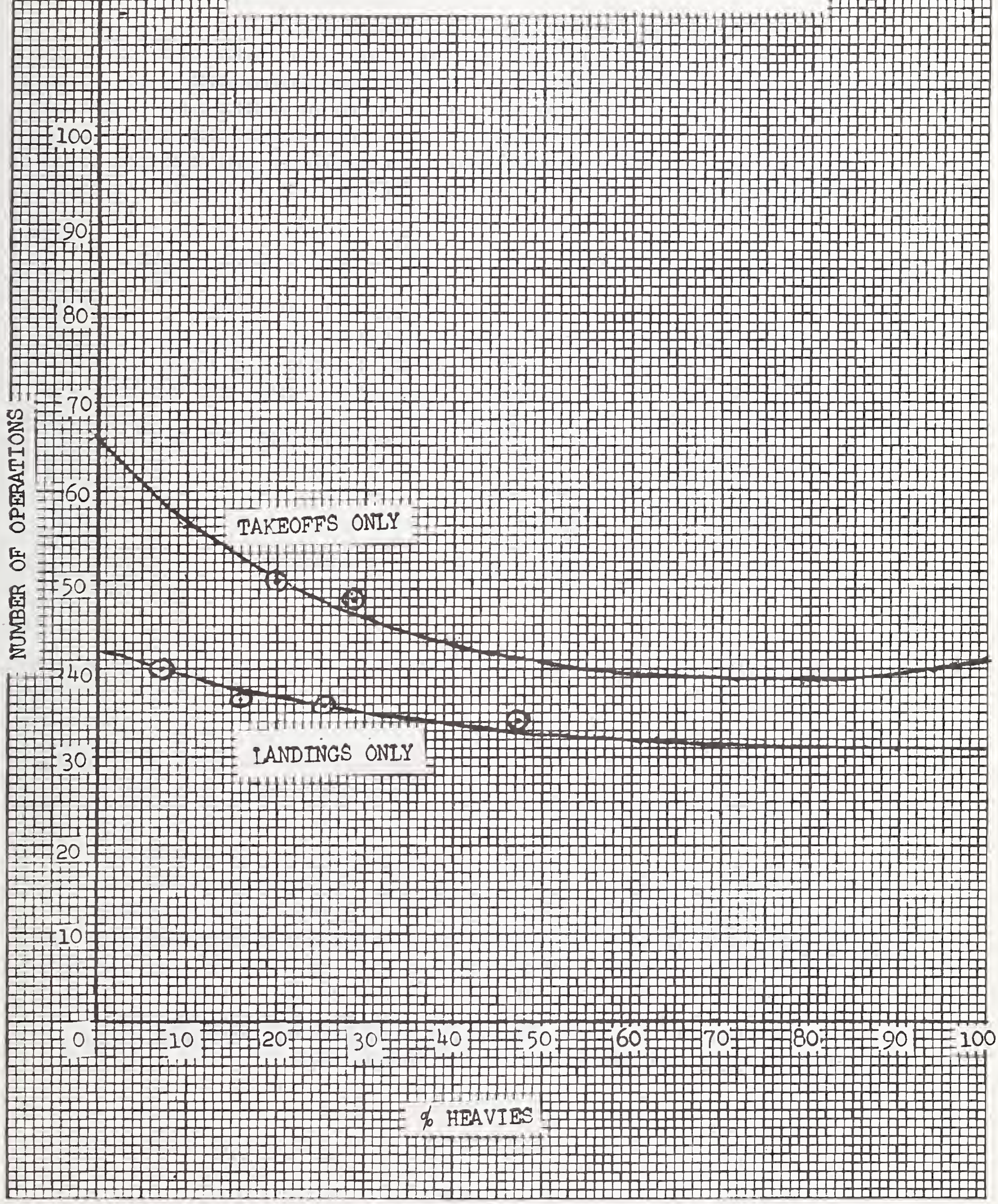
For r = 33 seconds, Δ = 54 seconds, and δ = 90 seconds for example, the values in Table 2.1 yield

$$N = 3600/[-64p^2+99p+54].$$

This is plotted as the upper curve in Figure 2.1. The two circled points, at 20 and 30 percent heavies, give the results of actual DELCAP runs and agree well with the corresponding values from the preceding formula.

FIGURE 2.1

Hourly Throughput for a Single Runway Handling Only Takeoffs or Only Landings



Similarly, to calculate the expected throughput for a single runway handling landings only, under the further assumption that landing speeds for all aircraft types are equal, let

N = number of landings per hour,
p = fraction of landings which are heavies,
s = the landing speed (in knots) for all aircraft types. (Although landing speed does vary among aircraft types, the figures in Table 2.1 indicate that using one value is not a great deviation from reality. More complicated formulas can be derived for the case in which speed depends on aircraft type.)

Then it follows (cf. the separation criteria given on page 4) that:

1. The time between the landings of two heavies is 4/s, between a heavy and a following non-heavy is 5/s, and between a non-heavy and a following aircraft is 3/s.
2. A fraction p of the aircraft following a heavy are heavies, a fraction (1 - p) are non-heavies.
3. The expected number of hourly landings by heavies is pN; for non-heavies it is (1 - p)N.

Thus the following equation holds:

$$pN\,[\,p(4/s) + (1-p)(5/s)] + (1-p)\,N\,(3/s) = 1$$

or

$$N = s/(3 + 2p - p^2).$$

For s = 125 knots, for example,

$$N = 125/(3 + 2p - p^2),$$

which is plotted on the lower curve in Figure 2.1. The four circled points, output from the DELCAP simulation, agree very well with the expected throughputs.

Analytical expressions can be and have been derived for more complicated operating policies involving dual operations (both landings and takeoffs),* but are much more complex since for some landing aircraft the minimum allowable spacing can be determined

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*See for example, W. A. Horn, Extension of a Capacity Concept to Dual-Use Runways and Multi-Runway Configurations, NBS Report 10593, April 1971.

by the separation from a preceding landing, rather than the separation from a takeoff occuring between the two landings. In this case, the takeoff is in some sense a "free" contribution to throughput since it does not require an extra interruption in the flow.

As part of our validation analysis, three operating policies for a dual use single runway were run using DELCAP. The output from these runs is displayed in Table 2.4. For time periods in which the numbers of arrivals and departures are approximately equal, the operating policy chosen for the single runway seeks to alternate landings and takeoffs. During departure-dominant periods, landings are spaced far enough apart to allow two takeoffs between each pair of landings. For arrival-dominant periods, takeoffs are permitted only between every other pair of landings.

As can be seen by comparing Table 2.4 with Figure 2.1, dual usage of the single runway decreases the takeoff throughput greatly (by about a factor of two). The reason is that landings require more time between operations and dual usage forces some takeoffs to wait for landings. On the other hand, landing throughput is not as greatly degraded by interspersing takeoffs among the landings. Alternation of landings and takeoffs decreased landing throughput by at most 30% from the pure landing operation, and increased total throughput by 40 - 60%. This agrees well with operating experience: in the absence of stringent takeoff-airspace restrictions, takeoffs are rarely the limiting throughput factor. On the other hand, spacing between landings is critical, and directions such as "maintain speed" sometimes have to be given by controllers to arriving aircraft in order to ensure that minimum spacing is attained.

Validation for the single-runway case was carried out because it is often an important component of more complicated configurations. Wide parallels may be regarded as two single runways in throughput calculations, for instance. Also, some airports may be reduced to essentially the single-runway configuration during IFR weather or outages. Still, the primary advantage of DELCAP lies in its applicability to more complex runway situations for which analytic expressions are much more difficult to obtain.

2.2.2 INTERSECTING RUNWAYS

Two different configurations consisting of a pair of intersecting runways were investigated: one with the intersection 2000 feet from the ends of each of the runways (representing the near-intersection or "V" case), the second with the intersection 4000 feet from the ends of each runway (a configuration shaped like an "X").

TABLE 2.4

Single Runway Throughput (per Hour)

OPERATING POLICY	RUNWAY	5% HEAVIES LAND	5% HEAVIES TAKEOFF	5% HEAVIES TOTAL	15% HEAVIES LAND	15% HEAVIES TAKEOFF	15% HEAVIES TOTAL	50 % HEAVIES LAND	50 % HEAVIES TAKEOFF	50 % HEAVIES TOTAL
ARRIVALS = DEPARTURES: ALTERNATE	1	28.2	28.2	56.4	27.3	27.3	54.6	26.3	26.3	52.6
DEPARTURES PREDOMINATE: TWO TAKEOFFS BETWEEN EACH PAIR OF LANDINGS	1	19.6	39.2	58.9	18.6	37.2	55.4	17.2	34.4	51.6
ARRIVALS PREDOMINATE: TWO LANDINGS BETWEEN EACH PAIR OF TAKEOFFS	1	32.8	16.4	49.3	31.7	15.8	47.5	29.2	14.5	43.7

During periods in which arrivals and departures are roughly balanced, two different operating policies were chosen as reasonable: the first of them alternates landings and takeoffs on both runways, while the second reserves one runway for landings only and the other just for takeoffs. (The second policy can result in lower capacity, but is easier for the controller and probably more representative of actual practice.) For departure-dominant periods, one of the runways handles takeoffs only, with landings and takeoffs alternated on the other. Similarly, for arrival-dominant periods, one runway is set aside for landings only, while landings and takeoffs alternate on the other.

Each intersecting-runway configuration was run both with and without the requirement that operations on one runway be separated from those on the other. In the less restrictive case, the only interaction imposed was that a landing's touchdown or a takeoff's start-of-roll on one runway could not occur in the period between a landing or start-of-roll of an aircraft on the other runway and the time that aircraft passed the intersection. In the other case, in addition to the preceding prohibition, landings on one runway had to be separated by the required 3, 4 or 5 miles from landings on the other, and also by 2 miles from preceding takeoffs on the other. Two separate tables are given for each of the V and X intersection cases (see Tables 2.5 - 2.8), one including the second separation requirement (described as "with interference") and one without.

The interference requirement drastically reduces throughput (by 25 - 45%), with the lower reduction occurring when takeoffs are allowed on only one runway (i.e., the middle two operating policies in the Tables). It is probably very unusual for landings to be allowed on both runways of an intersecting pair. In fact, the "landings on one, takeoffs on the other" policy is the one most often employed in practice for an intersecting pair, if the runways are of comparable length. When one is longer than the other, then segregation by aircraft type, rather than by operation, is often employed, and something approaching the policy of alternating operations might be achieved. In this case segregation by type (and thus by landing speed) would tend to decrease actual interlanding separation (by reducing gaps due to a slow plane following a faster one) resulting in slightly higher throughputs than those given in Tables 2.5 - 2.8. The maximum number of landings (which occurs for the policy allowing landings on both runways with takeoffs interspersed on one), with interference, is actually about the same as the number of landings on the landings-only runway alone (under the same policy) when there is no interference.

TABLE 2.5

Hourly Throughput for Near Intersection (V) With Interference

		5% HEAVIES			15% HEAVIES			50% HEAVIES		
OPERATING POLICY	RUNWAY	LAND	TAKEOFF	TOTAL	LAND	TAKEOFF	TOTAL	LAND	TAKEOFF	TOTAL
ARRIVALS = DEPARTURES	1	16.3	16.3	32.6	15.7	15.7	31.5	14.4	14.5	28.9
ALTERNATE ON BOTH	2	16.3	16.3	32.6	15.7	15.7	31.4	14.5	14.5	29.0
	TOTAL	32.6	32.6	65.3	31.5	31.4	62.9	28.9	29.0	57.9
ARRIVALS = DEPARTURES	1	0.0	49.0	49.0	0.0	44.7	44.7	0.0	40.8	40.8
RUNWAY 1-TAKEOFFS ONLY RUNWAY 2-LANDINGS ONLY	2	25.6	0.0	25.6	25.3	0.0	25.3	23.7	0.0	23.7
	TOTAL	25.6	49.0	74.7	25.3	44.7	70.0	23.7	40.8	64.6
DEPARTURES PREDOMINATE	1	0.0	44.4	44.4	0.0	41.4	41.4	0.0	37.8	37.8
RUNWAY 1-TAKEOFFS ONLY RUNWAY 2-ALTERNATE	2	22.4	22.4	44.9	22.1	22.0	44.1	21.7	21.6	43.3
	TOTAL	22.4	66.8	89.3	22.1	63.4	85.5	21.7	59.4	81.1
ARRIVALS PREDOMINATE	1	21.6	0.0	21.6	20.3	0.0	20.3	18.2	0.0	18.2
RUNWAY 1-LANDINGS ONLY RUNWAY 2-ALTERNATE	2	14.7	14.7	29.4	14.0	14.0	28.0	13.1	13.1	26.3
	TOTAL	36.3	14.7	51.0	34.3	14.0	48.3	31.4	13.1	44.5

TABLE 2.6

Hourly Throughput for Near Intersection (V) Without Interference

		5% HEAVIES			15% HEAVIES			50% HEAVIES		
OPERATING POLICY	RUNWAY	LAND	TAKOFF	TOTAL	LAND	TAKEOFF	TOTAL	LAND	TAKOFF	TOTAL
ARRIVALS = DEPARTURES	1	28.1	28.1	56.2	27.1	27.1	54.3	26.2	26.2	52.4
ALTERNATE ON BOTH	2	28.0	28.1	56.1	27.2	27.2	54.5	26.1	26.1	52.3
	TOTAL	56.2	56.2	112.4	54.4	54.4	108.8	52.3	52.4	104.7
ARRIVALS = DEPARTURES	1	0.0	63.4	63.4	0.0	54.2	54.2	0.0	46.7	46.7
RUNWAY 1-TAKEOFFS ONLY RUNWAY 2-LANDINGS ONLY	2	38.0	0.0	38.0	36.1	0.0	36.1	32.1	0.0	32.1
	TOTAL	38.0	63.4	101.4	36.1	54.2	90.4	32.1	46.7	78.8
DEPARTURES PREDOMINATE	1	0.0	63.8	63.8	0.0	54.7	54.7	0.0	46.7	46.7
RUNWAY 1-TAKEOFFS ONLY RUNWAY 2-ALTERNATE	2	27.9	28.0	55.9	27.1	27.1	54.3	26.1	26.1	52.3
	TOTAL	27.9	91.8	119.8	27.1	81.8	109.0	26.1	72.9	99.0
ARRIVALS PREDOMINATE	1	38.1	0.0	38.1	35.9	0.0	35.9	31.6	0.0	31.6
RUNWAY 1-LANDINGS ONLY RUNWAY 2-ALTERNATE	2	28.0	28.0	56.0	27.1	27.1	54.2	26.1	26.1	52.2
	TOTAL	66.1	28.0	94.1	63.1	27.1	90.2	57.7	26.1	83.8

TABLE 2.7

Hourly Throughput for Far Intersection (X) With Interference

OPERATING POLICY	RUNWAY	5% HEAVIES LAND	5% HEAVIES TAKEOFF	5% HEAVIES TOTAL	15% HEAVIES LAND	15% HEAVIES TAKEOFF	15% HEAVIES TOTAL	50% HEAVIES LAND	50% HEAVIES TAKEOFF	50% HEAVIES TOTAL
ARRIVALS = DEPARTURES	1	15.8	15.8	31.6	15.3	15.3	30.7	14.1	14.1	28.3
ALTERNATE ON BOTH	2	15.8	15.8	31.6	15.3	15.3	30.6	14.2	14.1	28.3
	TOTAL	31.6	31.6	63.2	30.6	30.7	61.3	28.3	28.3	56.6
ARRIVALS = DEPARTURES	1	0.0	44.8	44.8	0.0	41.4	41.4	0.0	38.2	38.2
RUNWAY 1-TAKEOFFS ONLY RUNWAY 2-LANDINGS ONLY	2	23.5	0.0	23.5	23.6	0.0	23.6	23.2	0.0	23.2
	TOTAL	23.5	44.8	68.3	23.6	41.4	65.0	23.2	38.2	61.4
DEPARTURES PREDOMINATE	1	0.0	42.7	42.7	0.0	40.0	40.0	0.0	36.8	36.8
RUNWAY 1-TAKEOFFS ONLY RUNWAY 2-ALTERNATE	2	21.5	21.5	43.1	21.4	21.4	42.8	21.3	21.3	42.7
	TOTAL	21.5	64.2	85.8	21.4	61.4	82.8	21.3	58.1	79.5
ARRIVALS PREDOMINATE	1	21.2	0.0	21.2	20.0	0.0	20.0	18.0	0.0	18.0
RUNWAY 1-LANDINGS ONLY RUNWAY 2-ALTERNATE	2	14.2	14.2	28.4	13.7	13.7	27.4	12.9	12.9	25.8
	TOTAL	35.4	14.2	49.6	33.7	13.7	47.4	30.9	12.9	43.8

TABLE 2.8

Hourly Throughput for Far Intersection (X) Without Interference

OPERATING POLICY	RUNWAY	5% HEAVIES LAND	5% HEAVIES TAKEOFF	5% HEAVIES TOTAL	15% HEAVIES LAND	15% HEAVIES TAKEOFF	15% HEAVIES TOTAL	50% HEAVIES LAND	50% HEAVIES TAKEOFF	50% HEAVIES TOTAL
ARRIVALS = DEPARTURES	1	27.2	27.2	54.5	26.3	26.2	52.5	25.4	25.4	50.9
ALTERNATE ON BOTH	2	27.2	27.3	54.5	26.4	26.4	52.8	25.5	25.4	50.9
	TOTAL	54.5	54.5	109.0	52.7	52.7	105.4	50.9	50.9	101.8
ARRIVALS = DEPARTURES	1	0.0	63.5	63.5	0.0	53.7	53.7	0.0	46.0	46.0
RUNWAY 1-TAKEOFFS ONLY RUNWAY 2-LANDINGS ONLY	2	35.1	0.0	35.1	34.5	0.0	34.5	31.2	0.0	31.2
	TOTAL	35.1	63.5	98.6	34.5	53.7	88.2	31.2	46.0	77.2
DEPARTURES PREDOMINATE	1	0.0	58.0	58.0	0.0	51.7	51.7	0.0	44.9	44.9
RUNWAY 1-TAKEOFFS ONLY RUNWAY 2-ALTERNATE	2	27.4	27.3	54.7	26.6	26.6	53.3	25.6	25.6	51.2
	TOTAL	27.4	85.3	112.7	26.6	78.4	105.0	25.6	70.5	96.1
ARRIVALS PREDOMINATE	1	38.0	0.0	38.0	35.3	0.0	35.3	30.8	0.0	30.8
RUNWAY 1-LANDINGS ONLY RUNWAY 2-ALTERNATE	2	26.3	26.4	52.7	26.1	26.0	52.1	25.5	25.5	51.0
	TOTAL	64.3	26.4	90.7	61.4	26.0	87.4	56.3	25.5	81.8

When the interference requirement is in force, the simulated throughput for the pure-landing/pure-takeoff policy is greater than that achievable from alternating landings and takeoffs on both runways, lending quantitative support to the policy most often used for this configuration. The total number of landings is decreased by about 25 percent but this is more than made up by a 30 percent increase in takeoffs. The "pure" policy results in many more takeoffs than landings (sometimes almost twice as many),and is thus not as effective when the numbers of landings and takeoffs are approximately in balance.

The difference between 5 and 50 percent heavies in the aircraft type mix leads to a decrease of 7 - 22% in total throughput, with the larger differences generally occurring for the policy having only landings on one runway and only takeoffs on the other. To explain this, note that with landings spaced at 5 miles (as for a non-heavy aircraft following a heavy), a takeoff can occur between the two landings without affecting either. The pure-landing/pure-takeoff policy does not exploit this, so that the full brunt of the increased separation is felt. Policies employing dual-use runways are in a better position to utilize these extra spaces.

The location of the intersection, far rather than near, causes a greater reduction in takeoff throughput than in landing throughput. This is to be expected, since runway occupancy time is not a critical factor in interlanding spacing, but plays a much greater role in constraining takeoffs. The intersection's location, however, has much less effect than does operating policy.

In summary, the simulated behavior of a pair of intersecting runways is very much as one would expect from logic and real-world experience. The throughput levels produced by DELCAP may be higher than those usually observed because two of the four operating policies simulated allow landings on both runways, a situation atypical in practice. The predicted throughputs for the pure-landing/pure-takeoff strategy perhaps represent the most realistic estimates. Since actual operating rules require aircraft to remain separated, one would expect the throughputs calculated with interference to be more like actual levels, except in those situations where one of the two runways handles primarily smaller aircraft under VFR rules (to which the IFR separations do not apply).

2.2.3 CLOSE PARALLELS

A parallel runway configuration was run under the restriction that landings on one runway must be separated by 3, 4 or 5 miles from landings on the other, and by 2 miles from preceding takeoffs on the other. (This restriction presently applies to parallels whose center lines are separated by 3000 - 4300 feet.) The results are given in Table 2.9.

During periods when the numbers of arrivals and departures are about the same, the operating policy of choice is to alternate landings and takeoffs on both runways. When departures predominate, one runway is reserved exclusively for them, while the other handles only landings. For periods in which arrivals predominate, one runway is restricted to landings only, while landings and takeoffs alternate on the other.

Comparison with Table 2.6 shows that the performance of a pair of close parallel runways very closely resembles that of a "V" intersection with interference, and many of the remarks made for that earlier case also apply here. Since runway occupancy time is not a critical factor in interlanding spacing and the required separations between landings on the two runways are the same as for one runway, the maximum landing throughput is effectively the same for a set of parallels as for a single runway. For this reason, the third configuration, which allows landings on both runways, has approximately the same throughput as a single runway with two landings between each pair of takeoffs (see Table 2.4). Alternating landings and takeoffs on both runways yields about a 16% improvement over the single runway, gained presumably because runway occupancy time has no effect on the other runway's operations. The greatest total throughput is attained by segregating the operation types, with only landings on one runway and only takeoffs on the other, but this results in only half as many landings as takeoffs, and so such a high level of throughput could not be sustained. The addition of the second of a close parallel pair of runways thus buys some additional throughput, 16% for periods when the numbers of arrivals and departures balance and 37% when departures dominate. During arrival-dominated periods, however, only 9% increase in total throughput is observed.

2.2.4 CLOSE PARALLELS WITH AN INTERSECTING RUNWAY

The runway configuration for these runs is pictured in Figure 2.2. For time periods in which arrivals and departures are balanced, the operating policy chosen reserves one of the parallel runways (1) for takeoffs, the other parallel (2) for landings and alternates landings and takeoffs on the crossing runway (3). For departure-dominant periods one of the parallels (1) is reserved for takeoffs,

TABLE 2.9

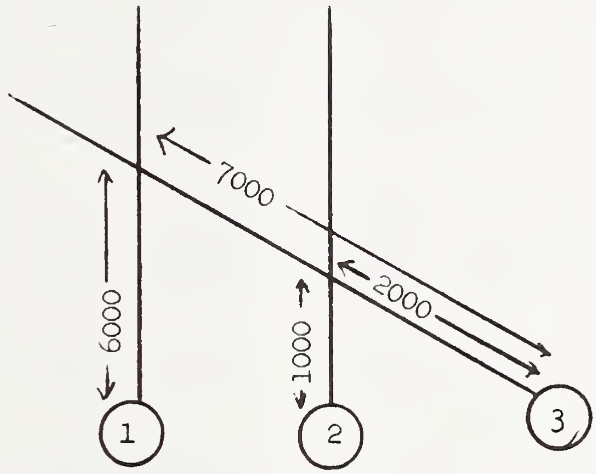
Hourly Throughput for Close Parallels

OPERATING POLICY	RUNWAY	5% HEAVIES LAND	5% HEAVIES TAKEOFF	5% HEAVIES TOTAL	15% HEAVIES LAND	15% HEAVIES TAKEOFF	15% HEAVIES TOTAL	50% HEAVIES LAND	50% HEAVIES TAKEOFF	50% HEAVIES TOTAL
ARRIVALS = DEPARTURES	1	16.3	16.4	32.7	15.7	15.7	31.5	14.5	14.5	29.0
ALTERNATE ON BOTH RUNWAYS	2	16.3	16.3	32.7	15.7	15.7	31.5	14.5	14.5	29.0
	TOTAL	32.7	32.7	65.4	31.5	31.5	63.0	29.0	29.0	58.0
DEPARTURES PREDOMINATE	1	0.0	54.0	54.0	0.0	49.0	49.0	0.0	42.3	42.3
RUNWAY 1-TAKEOFFS ONLY RUNWAY 2-LANDINGS ONLY	2	27.5	0.0	27.5	26.2	0.0	26.2	23.9	0.0	23.9
	TOTAL	27.5	54.0	81.6	26.2	49.0	75.2	23.9	42.3	66.2
ARRIVALS PREDOMINATE	1	16.5	16.5	33.1	16.0	16.0	32.0	13.8	13.8	27.6
RUNWAY 1-ALTERNATE RUNWAY 2-LANDINGS ONLY	2	21.0	0.0	21.0	20.0	0.0	20.0	18.7	0.0	18.7
	TOTAL	37.7	16.5	54.2	36.1	16.0	52.1	32.5	13.8	46.3

and landings and takeoffs are alternated on the other two runways. For arrival-dominant periods one of the parallels (1) is reserved for landings, and landings and takeoffs are alternated on the other two. These last two policies are probably unrealistically complicated for a real control situation, but have been simulated to show possible throughput advantages from dual operations.

FIGURE 2.2

Close Parallels with an Intersecting Runway



Tables 2.10 and 2.11 summarize the results of these runs. Separation requirements for aircraft on the two parallels are those described in Section 2.2.3 for close parallels. For the runs reported in Table 2.10, no interference requirements were put on the intersecting runway, so that takeoffs and landings on it were restricted only by runway occupancy on the other runways. This, of course, does not represent the real requirement when all runways are operated under IFR conditions, but may be more reflective of actual operating practice if the crossing runway is used primarily for smaller VFR aircraft. The runs reported in Table 2.11 had all interference restrictions in force.

Without the interference requirement in effect, the third runway increases landing throughput by 50 to 79% and takeoff throughput by 13 to 33% over the levels reported in Table 2.9 for parallel runways operated in the pure landing/pure takeoff mode. This increase does not accrue when the interference requirement is in force, since as noted earlier, on page 14 that requirement means that maximum landing throughput is effectively that of a single runway.

TABLE 2.10

Hourly Throughput for Close Parallels Plus an Intersecting Runway Without Interference

OPERATING POLICY	RUNWAY	5% HEAVIES LAND	5% HEAVIES TAKEOFF	5% HEAVIES TOTAL	15% HEAVIES LAND	15% HEAVIES TAKEOFF	15% HEAVIES TOTAL	50% HEAVIES LAND	50% HEAVIES TAKEOFF	50% HEAVIES TOTAL
ARRIVALS = DEPARTURES	1	0.0	40.3	40.3	0.0	36.6	36.6	0.0	34.9	34.9
RUNWAY 1-TAKEOFFS ONLY	2	21.2	0.0	21.2	21.3	0.0	21.3	21.6	0.0	21.6
RUNWAY 2-LANDINGS ONLY RUNWAY 3-ALTERNATE	3	20.9	20.9	41.8	20.8	20.8	41.6	21.0	21.0	42.1
	TOTAL	42.2	61.2	103.4	42.1	57.5	99.6	42.6	56.0	98.7
DEPARTURES PREDOMINATE	1	0.0	43.2	43.2	0.0	39.3	39.3	0.0	35.6	35.6
RUNWAY 1-TAKEOFFS ONLY	2	21.5	21.4	42.9	20.6	20.6	41.2	20.2	20.1	40.3
RUNWAY 2-ALTERNATE RUNWAY 3	3	22.8	22.8	45.6	22.9	22.9	45.8	22.0	22.0	44.0
	TOTAL	44.3	87.5	131.8	43.5	82.8	126.3	42.2	77.7	119.9
ARRIVALS PREDOMINATE	1	19.3	0.0	19.3	17.9	0.0	17.9	16.5	0.0	16.5
RUNWAY 1-LANDINGS ONLY	2	14.7	14.7	29.5	14.4	14.4	28.9	12.9	13.0	25.9
RUNWAY 2-ALTERNATE RUNWAY 3	3	15.2	15.2	30.4	15.3	15.3	30.7	14.5	14.5	29.0
	TOTAL	49.3	29.9	79.2	47.7	29.8	77.5	43.9	27.5	71.5

TABLE 2.11

Hourly Throughput for Close Parallels Plus an Intersecting Runway With Interference

OPERATING POLICY	RUNWAY	5% HEAVIES LAND	5% HEAVIES TAKEOFF	5% HEAVIES TOTAL	15% HEAVIES LAND	15% HEAVIES TAKEOFF	15% HEAVIES TOTAL	50% HEAVIES LAND	50% HEAVIES TAKEOFF	50% HEAVIES TOTAL
ARRIVALS = DEPARTURES	1	0.0	26.0	26.0	0.0	25.3	25.3	0.0	24.0	24.0
RUNWAY 1-TAKEOFFS ONLY	2	14.0	0.0	14.0	14.6	0.0	14.6	14.4	0.0	14.4
RUNWAY 2-LANDINGS ONLY	3	12.5	12.5	25.1	12.0	12.0	24.0	11.4	11.4	22.8
RUNWAY 3-ALTERNATE										
	TOTAL	26.5	38.6	65.1	26.7	37.3	64.0	25.8	35.4	61.3
DEPARTURES PREDOMINATE	1	0.0	30.4	30.4	0.0	26.1	26.1	0.0	24.6	24.6
RUNWAY 1-TAKEOFFS ONLY	2	12.7	12.7	25.4	11.9	11.8	23.7	11.6	11.5	23.1
RUNWAY 2-ALTERNATE RUNWAY 3	3	12.7	12.7	25.4	11.8	11.8	23.7	11.5	11.5	23.0
	TOTAL	25.4	55.8	81.3	23.7	49.8	73.5	23.1	47.7	70.8
ARRIVALS PREDOMINATE	1	15.3	0.0	15.3	14.3	0.0	14.3	12.6	0.0	12.6
RUNWAY 1-LANDINGS ONLY	2	9.4	9.4	18.9	9.5	9.4	18.9	9.0	9.0	18.1
RUNWAY 2-ALTERNATE RUNWAY 3	3	9.4	9.4	18.9	9.4	9.4	18.8	8.9	8.9	17.8
	TOTAL	34.2	18.9	53.1	33.2	18.8	52.0	30.5	17.9	48.5

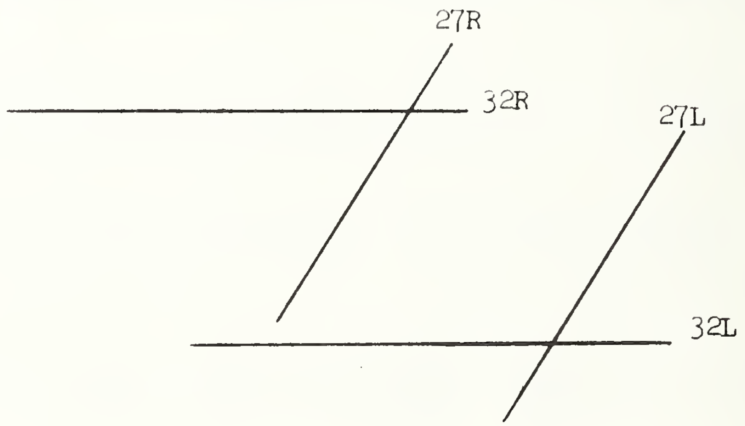
The three different operating policies chosen differ by 17 to 34% in landing throughput, but by a factor of almost 3 in takeoff throughput, again demonstrating that meeting takeoff demand is less difficult and less critical than meeting landing demand, a fact well-recognized by controllers. This is shown even more dramatically by the observation that the first and second policies displayed in Table 2.10 differ only in that the first one restricts runway 2 to landings only (rather than dual use), but the landing throughput is almost the same in the two cases.

2.3 Summary

The preceding section described output from applications of the DELCAP model to a variety of common runway configurations, demonstrating the model's versatility and its ability to represent those airport facilities for which further computerized throughput analysis is desired. DELCAP has also been run on the Chicago O'Hare (ORD) configuration depicted in Figure 2.3. In addition, the model is capable of handling even more complex configurations than this, with many more runways and more complicated interactions among them.

FIGURE 2.3

O' Hare Four-Runway Configuration



In the analyses reported above, the model was also exercised under different aircraft-type mixes and different arrival/departure ratios to demonstrate its ability to model these variations successfully. Changing the fraction of heavy aircraft from 5 to 50 percent decreases landing throughput (per runway per hour) by from 0 to 16% with an average decrease of about 9%, representing from 0 to 8 landings per runway and averaging about 3. Hourly takeoff throughput per runway is decreased more severely - from 0 to 28%, averaging 12% and representing a decrease of from 0 to 19 takeoffs (averaging 7).

As noted above, operating policy has almost as great an effect on throughput as does runway configuration. The influence of policy, a critical factor in actual operations, is probably somewhat exaggerated by the simulation when used to estimate maximum throughputs. In the simulation, operating policy is rigidly imposed. Whereas in a real situation a controller might run overflow takeoffs on a runway normally handling landings only, or divert a landing to a runway generally reserved for takeoffs, the simulation does not have this flexibility. In practice, the controller's extra leeway should allow him to exceed the capacity levels predicted by the model and therefore should allow for contingencies unforseen by model assumptions, such as more serious bunching of arrivals and departures, or gaps caused by pilot decisions over which the ATC system has little control. The comparative rigidity of the DELCAP model's handling of operating policy should not seriously affect its usefulness as a tool in establishing performance measures, if care is taken in its application to ensure the most appropriate policy is chosen for simulation.

The DELCAP simulation as now constituted assumes interlanding spacings of exactly 3, 4 or 5 miles as well as fixed and constant runway occupancy times, assumptions which are unrealistic. However, since real separations and runway occupancies may be either less or greater than the nominal values, it is unclear in which direction or to what extent these assumptions bias the resultant throughput values. In fact, it is not at all clear that much additional accuracy in throughput calculations would be gained from (the very easy-to-implement step of) representing these factors in a stochastic manner, particularly since results are averaged over a period of 20 hours.

Throughputs calculated by DELCAP vary with operating policy, configuration and mix in the expected direction and agree quite well in magnitude with observed levels. (A more complete description of this follows in the next section.) There are, however, a number of instances in which model outputs are higher than those actually attained at most installations. These involved the simulation of operating policies more complex in their control requirements than the policies in present use, so that empirical data with which to compare these outputs are lacking. For example, it would be unusual for a pair of intersecting or close parallel runways to be operated for any prolonged time with landings on both, unless one runway handled primarily smaller aircraft making visual approaches. This also holds true for the "parallels with crossing runway" configuration; most airports with such a configuration would use the parallels for landings and takeoffs (on separate runways) of larger aircraft, with the crossing runway allocated to lighter aircraft as required. The DELCAP throughputs reported above, therefore, in part require demand levels and controller capabilities which are unlikely to be sustained over long periods. More practical capacity levels are associated with those policies which reserve main runways for pure operations and shorter crossing runways for mixed operations of lighter aircraft.

3. COMPARISONS OF MODEL OUTPUT WITH AVAILABLE DATA

Table 3.1 reports IFR throughput figures for a variety of runway configurations at several airports, as computed by a theoretical procedure now under development by the FAA Air Traffic Service, as estimated by staff at the facility, and finally, as found using a version of the theoretical procedure devised by the FAA to account for local variations. The figures vary from facility to facility for the same configuration because of differences in aircraft-type mix and in other special characteristics such as air space restrictions (at JFK, for example). Differences between the theoretical and the modified standard values range from 4 to 19% and average 11%, so that one can regard as acceptable similar differences between these values and those produced by the model.

TABLE 3.1

Throughput for Several Configurations at Selected Airports

Configuration Class	Theoretical	Facility Estimates	Modified Standard
Wide Parallels			
. JFK IFR-Pure*	74	70	71
. MIA - Mixed	106	75	100
. ATL - Mixed	114	91	98
. ORD - Mixed	104	90	92
Close Parallels			
. JFK IFR -Pure	60	50	52
. PHL - Pure	68	52	57
4 R/W's			
2 Pure Approach 2 Pure Dept. ORD	152	135	137

* A "pure" operation is one handling only takeoffs or only landings. Parallels operated in a pure policy have one runway for only landings and a second only for takeoffs. "Mixed" operations refers to a policy allowing both landings and takeoffs.

In comparing the figures in Table 3.1 with DELCAP outputs, we have modified the latter to take into account the fact that takeoff capacity is rarely restricted and that the numbers in Table 3.1 are those sustainable over an extended period of time during which the total numbers of arrivals and departures are approximately equal. Whenever simulated takeoffs substantially outnumber landings, the maximum total throughput as calculated by DELCAP does not correspond to such a sustainable situation, and a better approximation to realistic total throughput is twice the calculated landing throughput. Table 3.2 reports throughputs thus obtained from DELCAP for configurations similar to those in Table 3.1. (Most of these numbers are taken directly from tables in the previous chapter.) Throughput for the wide parallels with pure operations, is calculated by adding the throughput for a single runway with only landings, to that for a single runway with only takeoffs.* Throughput for wide parallels used in mixed operations, is calculated as twice the landing throughput for a single runway serving alternating landings and takeoffs. Throughput for the ORD 4-parallels case pictured in Figure 2.3, is estimated as twice the landing throughput for a near-intersection ("V") configuration plus twice the landing throughput for a far intersection pair of parallels (both pairs without interference).

Differences in throughput among airports depend in part on the aircraft type mix. The mix at JFK contains approximately 43% heavies, while that at the other airports is much lower. (At ORD for instance, there are about 16 percent heavies.) For most of the airports of concern here, small aircraft account for a relatively small proportion of traffic (except for PHL where they account for about 40 percent). Therefore, for most airports the throughput figures are more like those reported for 5 and 15 percent heavies.

In the case of wide parallels and pure operations, values in the two tables agree quite well. Whereas the theoretical value of 74 operations per hour agrees exactly with the DELCAP value for 15 percent heavies, the value of 65 from DELCAP for 50 percent heavies is more appropriate since JFK has over 40 percent heavies. Linear interpolation (of 40% between 15 and 50%) yields about 68, slightly lower than the final figure of 71 (surprisingly, since one would normally expect the model, requiring perfect controllability, to estimate higher than actual values), but still within 5 or 6 percent of the modified performance standard.

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*The numbers in Table 3.2 for this case are obtained from runs not reported in Chapter 2.

TABLE 3.2

Sustainable Throughput Estimated by DELCAP

CONFIGURATION AND POLICY	5% HEAVIES				15% HEAVIES				50% HEAVIES			
	LAND	TAKEOFF	TOTAL	SUSTAIN	LAND	TAKEOFF	TOTAL	SUSTAIN	LAND	TAKEOFF	TOTAL	SUSTAIN
WIDE PARALLELS PURE	38.8	61.3	100.1	77.6	36.8	53.9	90.7	73.6	32.3	45.7	68.0	64.6
WIDE PARALLELS MIXED	56.4	56.4	112.8	112.8	54.6	54.6	109.2	109.2	52.6	52.6	105.2	105.2
CLOSE PARALLELS PURE	27.5	54.0	81.6	55.0	26.2	49.0	75.2	52.4	24.9	42.3	66.2	49.8
2 WIDE PARALLELS (ORD) PURE	73.1	126.9	200.0	146.2	70.6	107.9	178.5	141.2	63.3	92.7	156.0	126.6

In the case of wide parallels under mixed operations, DELCAP maximum throughput values vary from 105 for 50% heavies to 113 for 5% heavies, agreeing very well with the 104 to 114 theoretical values for the three airports using this operating policy. The most applicable DELCAP values are for the 5 to 15% heavies for these three airports, meaning that DELCAP estimates are 5 to 7 operations high for MIA (Miami International) and ORD (Chicago O'Hare International), and one operation low for ATL (Atlanta), but still within 5 to 6% of the theoretical values determined by the FAA.

The throughputs calculated by DELCAP agree surprisingly well with those of the modified standard for close parallels, with the DELCAP values ranging from 55 to 50 and the standards between 57 and 52. DELCAP values are somewhat lower than the theoretical ones. Most serious for DELCAP's use is that the throughput rates (obtained by doubling landing rates) for close parallels are lower than those obtained for a single runway alternating operations. This occurs because DELCAP presently simulates "operating policies" only as defined for individual runways, without coordination; operations on the two runways are treated separately, with only their interferences being modeled. Since the minimum separation time between takeoffs is less than that between landings (for the speeds in Table 2.1), DELCAP allows about 80 percent more takeoffs than landings. These extra takeoffs lower the number of landings, since the interference rules require landings to be separated by 2 miles from takeoffs on the other runway. This can be remedied by modifying DELCAP to allow for an operating policy which applies to a pair of runways together. Such a policy would more closely mirror actual operating practice, which tends to follow a landing on one parallel or intersecting runway with a takeoff on the other. With such a policy in effect, throughput for a set of close parallels under pure operations could be expected to be slightly more than the 52 to 56 operations/hr. available from a single runway alternating operations, and thus would more closely approximate the theoretical estimates of Table 3.1.

Throughput calculated by DELCAP for the 4-runway ORD case lies between the modified standard and the theoretical value in Table 3.2. Note that the DELCAP throughputs used for this analysis are those without interference. (If values from runs with interference were used, the DELCAP estimates would be considerably lower. As in the case of the close parallels above, the landing throughput predicted by DELCAP for intersecting runways with interference is degraded because of the extra takeoffs generated when the model independently schedules operations on the two runways.) Discussions with FAA personnel familiar with the ORD operation indicate that the two sets of parallels are treated almost as two independent sets of intersecting runways. For the pure operating policy, takeoffs are cleared once a landing passes the intersection and occur in such a way that the two mile departure/arrival separation does not limit operations. In this operating situation the "without interference" policy more closely describes the actual situation and is therefore indeed the more appropriate policy choice for comparison purposes.

3.1 Summary

On the whole, the throughput levels calculated by DELCAP agree quite well with accepted values for several common configurations, with one identified exception, concerning the model's independent scheduling of traffic on two close parallel or intersecting runways with interference rules in effect. Since landing capacity is so much smaller than takeoff capacity, such scheduling results in almost twice as many takeoffs as landings. The interference rules require landings to be separated by two miles from preceding takeoffs on the other runway, and so the extra takeoffs force landings to be separated by more than the minimum spacing. The remedy suggested above is that of modifying DELCAP to permit the specification of an operating policy for a pair of runways, in much the same manner that policies are now specified for each runway singly. This would allow the alternation of landings on one runway with takeoffs on the other. An additional benefit would be the ability, for many configurations, to specify ratio of landings to takeoffs, since as long as input traffic levels are high enough to insure no gaps in either landings or takeoffs, the operating policy completely determines the sequence of operations performed. Such a procedure would lessen the necessity observed above for makeshift calculation of total throughput as twice the number of landings, but rather would provide a balanced output directly.

Besides identifying the need for the modification noted above, and for great care in defining the actual operating policies on which "observed" data are based, the exercises reported in the previous chapter have demonstrated the versatility of DELCAP and the general agreement of its throughput calculations with a set independently arrived at, thus increasing confidence in the model's validity.

The exercises described above have incorporated some preliminary investigation of model throughput sensitivity to aircraft mix and to runway operating policy. Throughput decreases, from 10 to 33 percent (averaging about 16), as the percentage of heavy aircraft in the mix increases from 5 to 50 percent. Of much greater effect on throughput are two other factors: runway operating policy, and the interference requirements. The latter is determined by ATC rules, but only applies to IFR traffic. If some crossing runways are used primarily by VFR aircraft, or many aircraft are able to turn off before an intersection, then throughput obtained from DELCAP runs without interference rules in effect would more closely represent the actual situation.

As has been noted above, care must be taken in defining the operating policy. Throughput for wide parallels with alternating operations on both runways is 113, while that for wide parallels handling pure operations is 78. Depending on the actual sequencing of operations on the two runways, almost any value between these two extremes can be obtained. Therefore it is necessary to be very careful in defining the operating policy to insure that the DELCAP runs model the particular situation desired, and it is perhaps most desirable to try a variety of policies if there is any question as to which is most applicable.

The DELCAP simulation as now consituted assumes interlanding spacings of exactly 3, 4 or 5 miles as well as fixed and constant runway occupancy times, assumptions which are unrealistic. However, the validation indicates that not much additional accuracy in throughput calculations would be gained from (the very easy-to-implement step of) representing these factors in a stochastic manner.

APPENDIX A

CHANGES AND ADDITIONS TO DELCAP

During the course of the validation effort reported in this document, modifications were made to the DELCAP model in four areas: output, separation criteria, operating policy, and random number generator. None of the changes required extensive recoding, a feature which was one of the major factors in deciding which of a number of plausible changes should be implemented. A second factor was the benefit expected to accrue and the priority of need for that change. A further description of the changes is given below, and is followed by a more detailed description of the alterations in the actual computer coding of the preprocessor and simulation.

A.1 Description of Modifications

DELCAP is expected to operate under two scenarios: one to compute airport maximum throughput (capacity) and the second to compute delay resulting from a particular demand profile. Since delay output would be meaningless under the first scenario, the user now has the option of supressing delay output for runs under this scenario. Current output formats have been modified so that the number of characters per line is less than 72, permitting output to fit on most terminals. Output now consists of actual throughputs and average delay per aircraft for each hour, separately for landings, takeoffs and total operations, separately by runway. Summary statistics at the end of a run provide for each runway -- separately for landings, takeoffs and total operations -- the total throughput for the run, average hourly throughput and average total hourly delay. Illustrative maximum throughput output, for one hour of simulated time at the ORD configuration depicted in Figure 2.3, is given in Figure A.1. Figure A.2 displays both throughput and delay figures for a single runway for 20 hours of operation. In addition to throughput and delay information, DELCAP prints the final random number seed for use in subsequent runs. (See below for a more complete description of the random number generation process.)

With the advent of heavy aircraft (greater than 300,000 lbs. gross weight) wake turbulence problems have led to the imposition of separation rules requiring 5 mile separation for all non-heavy aircraft landing following a heavy, and 4 mile separation for a heavy following a heavy. All other aircraft combinations must be separated by 3 miles. Any non-heavy taking off behind a heavy must wait for two minutes after the heavy lifts off. Other takeoff separations are

FIGURE A.1

Throughput Output for One Hour at ORD

HOUR	RUNWAY	HOURLY THROUGHPUT LANDINGS	TAKEOFFS	TOTAL
17	1	29	0	29
	2	0	39	39
	3	0	35	35
	4	33	0	33

FINAL RANDOM NUMBER SEED 2123422532[illegible]1

SUMMARY REPORT FOR THIS RUN

TOTAL THROUGHPUT

RUNWAY	OPERATIONS PERFORMED LANDINGS	TAKEOFFS	TOTAL
1	29	0	29
2	0	39	39
3	0	35	35
4	33	0	33
TOTAL	62	74	136

AVERAGE HOURLY THROUGHPUT

RUNWAY	OPERATIONS PERFORMED LANDINGS	TAKEOFFS	TOTAL
1	29.	0.	29.
2	0.	39.	39.
3	0.	35.	35.
4	33.	0.	33.
TOTAL	62.	74.	136.

FIGURE A.2

Hourly Throughput and Delay for a Single Runway for 20 Hours

HOUR	RUNWAY	HOURLY THROUGHPUT LANDINGS	TAKEOFFS	TOTAL	HOURLY DELAY* PER AIRCRAFT LANDINGS	TAKEOFFS	ALL
3	1	7	17	24	2.5	4.1	3.6
4	1	9	12	21	2.6	3.0	2.9
5	1	4	8	12	0.0	2.3	1.6
6	1	8	11	19	0.6	5.5	3.4
7	1	13	8	21	1.7	5.5	3.1
8	1	13	5	18	1.0	3.0	1.6
9	1	7	14	21	0.1	7.0	4.7
10	1	16	11	27	1.5	3.8	2.4
11	1	15	11	26	3.7	4.6	4.1
12	1	6	10	16	0.3	3.0	2.0
13	1	5	8	13	0.3	3.5	2.3
14	1	6	14	20	0.2	2.1	1.6
15	1	9	8	17	0.3	2.6	1.4
16	1	14	11	25	0.8	3.8	2.1
17	1	12	11	23	1.0	4.7	2.8
18	1	13	9	22	0.9	4.8	2.5
19	1	19	8	27	1.9	3.8	2.5
20	1	15	8	23	2.4	3.8	2.9
21	1	7	4	11	0.8	2.6	1.4
22	1	4	9	13	0.	2.6	1.8

FINAL RANDOM NUMBER SEED 270022620225

* Delay is measured in minutes.

FIGURE A.2 (CONTINUED)

Summary of Throughput and Delay for the Single Runway of Figure A.2

SUMMARY REPORT FOR THIS RUN

TOTAL THROUGHPUT

RUNWAY	OPERATIONS PERFORMED		
	LANDINGS	TAKEOFFS	TOTAL
1	202	197	399
TOTAL	202	197	399

AVERAGE HOURLY THROUGHPUT

RUNWAY	OPERATIONS PERFORMED		
	LANDINGS	TAKEOFFS	TOTAL
1	10.1	9.8	19.9
TOTAL	10.1	9.8	19.9

AVERAGE HOURLY DELAY

RUNWAY	DELAY (MINUTES)		
	LANDINGS	TAKEOFFS	TOTAL
1	14.0	38.7	52.7
TOTAL	14.0	38.7	52.7

approximated in DELCAP by requiring that the second aircraft wait 30 seconds after the first lifts off. This eliminates all references to whether aircraft diverge or not and all necessity for treating departure paths. Other landing and takeoff separations may be input if it is so desired, but the revised DELCAP allows separation to depend only on the types of aircraft involved.

Early test runs of DELCAP indicated that the random number generator available in the SIMSCRIPT system did not produce a sequence of numbers which were statistically "random" to a satisfactory degree. This has been remedied with the inclusion of a random number generator obtained from the NBS Statistical Engineering Laboratory. This generator requires a starting value (referred to as the "seed"), which is modified each time a random number is calculated. The final seed is printed out by DELCAP and can be used to start other runs. The sequence of random numbers produced depends entirely on the seed, so that runs can be replicated by using the same seed and on the other hand different traffic samples can be obtained by using different seeds. The seed is input and output as a 12 digit octal number.

The initial version of DELCAP allowed 4 different operating policies: landings only, takeoffs only, mixed operations where landings take precedence, and mixed operations in which landings and takeoffs alternate. To allow a more flexible sequencing procedure DELCAP was modified to allow the user to input the desired operation sequence. The user may provide any sequence of operations (of length up to 10) and this sequence will be repeated for the duration of the run.

A.2 Programming Details of the Modifications

The input stream to the preprocessor has been changed, and the complete new version appears in Table A.1. Only changes from the previously documented version* will be noted below.

1. INPUT is now dimensioned by 8 rather than 6, the two additional items being a switch to indicate whether a run is designed to output throughput only (INPUT(7)=0) or both throughput and delay (INPUT(7)=1), and the random number seed as a twelve digit octal number INPUT(8).

2. Separations SEPLL, SEPTT and SEP2 now depend on the leading and following aircraft types. This changes the input FORMATs and standard values which are the ones described above (3,4 and 5 miles for landings, 30 seconds or 2 minutes plus the runway occupancy time for takeoffs).

*Judith Gilsinn, E.H. Short, W.A. Steele and D. Klavan, A Simulation Model for Estimating Airport Terminal Area Throughputs and Delays, NBS Report 10592, May 1971.

TABLE A.1

Preprocessor Input Formats

Card No.	Column Nos.	Variable	No. Decimal Places	FORTRAN Format
1	1 - 7	TBEG - beginning of simulation	2	F7.2
	8 - 14	TEND - end of simulation	2	F7.2
2	1 - 18	INPUT (1 - 6), 3 columns per element	-	6A3
	19	print indicator (0=throughput, 1=both delay and throughput)	-	I1
	20-31	random number seed	-	012
GROUP I				
one per type	1 - 3	number of type (≤ 10)	0	I3
	4 - 6	= 0 if type has DME > 0 if type does not have DME	0	I3
	7 - 13	aver. landing speed(knots)	2	F7.2
	14 - 20	aver. takeoff speed(knots)	2	F7.2
	21 - 27	aver. runway occupancy time - landing -(seconds)	2	F7.2
	28-34	aver. runway occupancy time - takeoff - (seconds)	2	F7.2
#types + 1		end-of-file		
#types + 2	1 - 7	aver. turn-off speed, all types	2	F7.2

Card No.	Column Nos.	Variable	No. Decimal Places	FORTRAN Format
GROUP II				
1	6 per type	decimal fraction of take-off mix, of each type	4	12F6.4
2	same	dec. frac. of landing mix of each type	4	12F6.4
GROUP III				
1, 2	6 per hour	number of planes taking off per hour	1	12F6.1
3, 4	same	# planes landing per hour	1	12F6.1
GROUP IV				
1	1 - 7	distance to departure/ arrival fix	2	F7.2
	8-14	required separation between an arrival and a departure	2	F7.2
2 through $\frac{NTYP \times NTYP}{10}$	7 per type pair	required separation between landing aircraft	2	10F7.2

Card No.	Column Nos.	Variable	No. Decimal Places	FORTRAN Format
GROUP V				
one per runway	1 - 2	number of runways (1 - 9)	0	I2
	3 - 6	heading of runway	0	I4
	7 - 8	left/right designation	-	A2
	9 - 12	operation code: 1-takeoffs only, 2-landings only, 3-both, alternating 4-both, landings preferred	0	I4
	13 - 19	distance to outer marker (naut. miles)	2	F7.2
#rw +1		end-of-file		
one per runway with OPER>4	1-2	number of operations in sequence	-	I2
	2 per operat.	operation sequence (1=takeoff;2=landing).	-	I2
one per runway	7 per type	time, in minutes, for each type to fly from handoff to outer marker	2	10F7.2
one per inter-section	1 - 2	first runway number	0	I2
	3 - 4	second runway number	0	I2
	5 - 12	distance from end of first to intersection (feet)	0	F8.0
	13 - 20	distance from end of se-cond to intersection (feet)	0	F8.0
		end-of-file		

Card No.	Column Nos.	Variable	No. Decimal Places	FORTRAN Format
one per inter-ference	1 - 2	first runway	0	I2
	3 - 4	second runway	0	I2
	5 - 6	interference code: 1 - simultaneous dep/arr and dep/dep are permitted, given divergence, but arr/arr is prohibited, 2 - all simultaneous operations prohibited.	0	I2
		end-of-file		
GROUP VI				
one per type	6 per runway	decimal fraction of all takeoffs of type which use each runway, followed by decimal fraction of all landings of type which use each runway	4	12F6.4

3. For each runway with OPER > 4, the user must specify the sequence of operations for that runway.

4. All references to departure paths have been deleted.

5. The preprocessor has also been modified to agree with the new version of DELCAP, so that there are now 55 arrays and the new variables are correctly initialized in proper order.

New variables and arrays appearing in the DELCAP simulation are described in Table A.2, together with their array numbers and dimensions.

Two FORTRAN subroutines are used by DELCAP in obtaining random numbers, RANDOM and RNG. RNG is called by event routines BEGIN and GEN and functions PTYPE and PRWAY. RANDOM is called by RNG. The calling sequence for RNG is (**INITR,*R,1,0), where INITR is the random number seed, R is the random number drawn, 1 is the number of random numbers to be drawn at each call and 0 indicates that R is to be drawn from a uniform distribution. Note that variables with no asterisks are input to the subroutine only, variables with one asterisk are output only, and those with two asterisks are both input and output.

Other modifications to the DELCAP simulation include changes to LAND and TOFF to accommodate the new separation procedures, changes to NXTOP, LAND and TOFF to effect the more flexible sequencing policy, and changes to CHOUR and PRINT to accumulate and print the new output versions.

A revised listing including the changes reported in this Appendix appears below as Appendix B. Further inquiries and requests for computer card decks of the DELCAP simulation and preprocessor should be directed to:

Judith F. Gilsinn
Room A428, Administration Building
National Bureau of Standards
Washington, D.C. 20234
(Telephone: AC 301-921-3431)

TABLE A.2

New and Changed Arrays in DELCAP

Array Number	Array Name	Dimensions	Description
4	CAP	--	indicates whether to print only throughput (CAP=0) or both throughput and delay (CAP=1)
18	SEPLL	type X type	interlanding separation
32	SEPTT	type X type	intertakeoff separation
51	TDRW	runway X operation	total delay accumulated for the run
52	HDRW	runway X operation	hourly delay
53	TNRW	runway X operation	total number of operations for the run
54	HNRW	runway X operation	hourly operation counts
23	SQOP	runway X index	operation sequence for each runway with OPER > 5
25	LAST	runway	index of next operation in sequence for runways with OPER > 5
55	INITR	--	random number seed

APPENDIX B

NEW DELCAP PROGRAM LISTING

```
+N  GEN   4        N  RWAY   31  2  I    1Q      F            Q    2 F          PTYPEI
+N  NXTOP4         N  OP     32  2  I    2RW     F                              PRWAYI
+N  LAND  4                              3TYP    F
+N  TOFF  4                              4CAP    0     I                        FREERF
+                  N  PT     4      I    5H      F
+N  FTIUP4         T  TYPE   1      I    6OPER   1     I
+N  PRINT4         N  DLAY   4      F    7DOM    1     F
+T  FLT   4        T  TIN    3      F    8NPT    1     I
+T  TIEUP4                               9FLYOM  2     F
+N  ENDS  2        T  TMIN   1      F   10DME    1     I
+N  CHOUR2         T  TMAX   2      F   11VLAND  1     F
+                                       12VTOFF  1     F
+                                       13ROTL   1     F
+                                       14ROTT   1     F
+                  T  SQ     4      I   15VTAXI  0     F
+                                       16DAFIX  0     F
+                                       17SEPLL  2     F
+                                       18SEPTL  0     F
+                                       19CALIN  1     F
+                                       20CTYPE  2     F
+                                       21CRWYT  2     F
+                                       22CRWYL  2     F
+                                       23SQOP   2     I
+                                       24NEXT   1     I
+                                       25LAST   1     I
+                                       26DINT   2     F
+                                       27FQ     2     I
+                                       28LQ     2     I
+                                       29RPT    2     I
+                                       30TPT    2     I
+                                       31TOMIN  1     F
+                                       32SEPTT  2     F
+                                       33NARR   1     I
+                                       34NDEP   1     I
+                                       35NLAND  1     I
+                                       36NTOFF  1     I
+                                       37DFLT   1     F
+                                       38DFLL   1     F
+                                       39TREG   0     F
+                  T  POMTI  3      I   40FOMTI  1     I      OMTI1   RTMAX   L
+                  T  SOMTI  4      I   41LOMTI  1     I      THTI1   RTMAX   L
+                  T  PTHTI  3      I   42FTHTI  1     I      ERTI1   RTMAX   L
+                  T  STHTI  4      I   43LTHTI  1     I
+                  T  PERTI  3      I   44FERTI  1     I
+                  T  SERTI  4      I   45LERTI  1     I
+                                       46TEND   0     F
+                                       47LAMBD  2     F
+                                       48IHOUR  0     I
+                                       49SEP2   2     F
+                                       50GENN   1     I
+                                       51TDRW   2     F
+                                       52HDRW   2     F
+                                       53TNRW   2     I
+                                       54HNRW   2     I
+                                       55INITR  0     I
```

```
EVENTS
 2 EXOGENOUS
   BEGIN (1)
   EXGEN (2)
 8 ENDOGENOUS
   GEN
   NXTOP
   LAND
   TOFF
   ETIUP
   CHOUR
   PRINT
   ENDS
END  EVENT LIST
```

```
      EXOGENOUS EVENT BEGIN
      DO TO 1, FOR EACH O I
      CREATE GEN
      STORE I IN OP(GEN)
      STORE GEN IN GENN(I)
      CALL RNG(**INITR,*R,1,0)
      LET T=TIME-LAMBD(I,IHOUR)*ALOG(1.-R)
      CAUSE GEN AT T
1     LOOP
      CREATE ENDS
      CAUSE ENDS AT TEND
      CREATE CHOUR
      CAUSE CHOUR AT TIME+1.
      IF CAP GT 0, GO TO 2
      WRITE ON TAPE 6
      FORMAT ('1',S20,'HOURLY THROUGHPUT'
     1/' HOUR   RUNWAY',S5,'LANDINGS TAKEOFFS   TOTAL'/)
      RETURN
2     WRITE ON TAPE 6
      FORMAT ('1',S20,'HOURLY THROUGHPUT',S9,'HOURLY DELAY PER AIRCRAFT'
     1/' HOUR   RUNWAY',S5,'LANDINGS TAKEOFFS   TOTAL',S5,
     2'LANDINGS TAKEOFFS     ALL'/)
      RETURN
      END BEGIN
```

```
      ENDOGENOUS EVENT GEN
C     GEN  GENERATES LANDINGS AND TAKEOFFS AND
C     ASSIGNS ATTRIBUTES TO THEM.
C     OP(GEN) IS 1- TAKEOFF , OR 2-LANDING
      STORE OP(GEN) IN I
C     GEN SCHEDULES ITSELF TO OCCUR AGAIN AFTER A TIME INTERVAL
C     DEPENDING ON THE RATE OF OPERATION.
      CALL RNG(**INITR,*R,1,0)
      CAUSE GEN AT TIME-LAMBD(I,IHOUR)*ALOG(1.-R)
      CREATE FLT
      LET IT=PTYPE(I)
      STORE IT IN TYPE(FLT)
      LET K=PRWAY(I,IT)
      GO TO (1,2),I
C     TIN(FLT)  IS THE TIME A FLIGHT IS AVAILABLE TO BEGIN FINAL
C     DESCENT (FOR LANDINGS) OR TO BEGIN TAXIING TO RUNWAY(FOR TAKEOFF)
C     CALIN IS A TIME LAG INTRODUCED IN TAKEOFFS, CORRESPONDING TO
C     FLYOM - THE TIME A LANDING TAKES TO FLY FROM
C     HANDOFF TO THE OUTER MARKER.
 1    LET TIN(FLT)=TIME+CALIN(K)
      GO TO 3
 2     LET TIN(FLT)=TIME+FLYOM(IT,K)
 3     IF Q(K,I) IS NOT EMPTY, GO TO 4
      CREATE NXTOP
      LET RWAY(NXTOP)=K
      CAUSE NXTOP AT TIN(FLT)
C     Q(K,I) - IS THE QUEUE OF PLANES WAITING TO TAKEOFF(I=1),
C     OR LAND(I=2) ON RUNWAY K.
 4    FILE FLT IN Q(K,I)
      RETURN
      END GEN
```

```
      EXOGENOUS EVENT EXGEN
C     EXGEN GENERATES EXPLICIT DEPARTURES AND ARRIVALS
      SAVE EVENT CARD
      CREATE FLT
      READ I,K,IT
      FORMAT (3I2)
      STORE IT IN TYPE(FLT)
      GO TO (1,2),I
1     LET TIN(FLT)=TIME+CALIN(K)
      GO TO 3
2     LET TIN(FLT)=TIME+FLYOM(IT,K)
3     IF  Q(K,I) IS NOT EMPTY, GO TO 4
      CREATE NXTOP
      LET RWAY(NXTOP)=K
      CAUSE NXTOP AT TIN(FLT)
4     FILE FLT IN Q(K,I)
      RETURN
      END
```

```
      FUNCTION PTYPF(I)
C     PTYPF CHOOSES AN AIRCRAFT TYPF FOR FACH FLIGHT ACCORDING  TO
C     CTYPF - THF CUMULATIVE DISTRIBUTION OF A/C TYPES IN THE MIX.
      CALL RNG(**INITR,*R,1,0)
      DO TO 1, FOR EACH TYP J
      IF R LE CTYPF(I,J), GO TO 2
1      LOOP
2     LET PTYPE=J
      RETURN
      END PTYPE
```

```
      FUNCTION PRWAY(I,M)
C     PRWAY CHOOSES A RUNWAY FOR EACH FLIGHT ACCORDING TO
C     CRWYL - THE CUMULATIVE DISTRIBUTION OF PRWYL(SEE PREPROCESSOR),OR
C     CRWYT - SAME AS CRWYL FOR TAKEOFFS.
      CALL RNG(**INITP,*R,1,0)
      DO TO 3, FOR EACH RW J
      GO TO (1,2),I
 1    IF R LE CRWYT(M,J), GO TO 4
      GO TO 3
 2    IF R LE CRWYL(M,J), GO TO 4
 3    LOOP
 4    LET PRWAY=J
      RETURN
      END PRWAY
```

```
      ENDOGENOUS EVENT NXTOP
C     NXTOP DECIDES WHICH OPERATION WILL BE SCHEDULED NEXT
C     ON EACH RUNWAY.
      STORE RWAY(NXTOP) IN K
      DESTROY NXTOP
C     IF NEXT NE 0, THE NEXT OPERATION HAS ALREADY BEEN DECIDED UPON.
      IF NEXT(K) NE 0, RETURN
      STORE OPER(K) IN J
      IF J GE 3, GO TO 1
      LET I=J
C     IF RUNWAY HANDLES ONLY ONE OPERATION, FIND NEXT FLIGHT
C     WAITING IN THE QUEUE AND SCHEDULE IT.
      FIND FIRST, FOR EACH FLT IN Q(K,I),IF NONE, RETURN
      STORE FLT IN F
      LET T=FREFER(K,I,F)
      GO TO 4
C     IF RUNWAY HANDLES BOTH OPERATIONS IN ALTERNATION, LOOK FOR
C     NEXT FLIGHT WAITING TO PERFORM THE ALTERNATE OPERATION.
 1    IF LAST(K) GT NSQOP(K), LET LAST(K)=1
      LET II=LAST(K)
      LET I=SQOP(K,II)
C     IF LANDINGS TAKE PRECEDENCE, ALWAYS CONSIDER THE
C     LAST OPERATION TO HAVE BEEN A TAKEOFF.
      IF I EQ 4, LET I=2
      LET T=-1.
      LET IFLAG=0
      LET TT=999999.
      FIND FIRST, FOR EACH FLT IN Q(K,I),IF NONE, GO TO 2
      STORE FLT IN F
      LET IFLAG=1
      LET T=FREFER(K,I,F)
      IF TIN(F) LS T, GO TO 4
      LET TT=T
      LET II=I
 2    LET I=I+1
      IF I GT 2, LET I=1
C     IF NO FLIGHT AVAILABLE NOW, SEARCH THE OTHER QUEUE.
      FIND FIRST, FOR EACH FLT IN Q(K,I),IF NONE, GO TO 3
      STORE FLT IN F
      LET IFLAG=1
      LET T=FREFER(K,I,F)
      IF TIN(F) LS T, GO TO 4
 3    IF IFLAG EQ 0, RETURN
C     IF NO FLIGHT THERE EITHER, CHOOSE THE FLIGHT WHICH
C     WILL BE AVAILABLE EARLIEST.
      IF T LT TT, GO TO 4
      LET T=TT
      LET I=II
```

```
4     LET NEXT(K)=I
      GO TO (5,6), I
5     CREATE TOFF
      STORE K IN RWAY(TOFF)
      CAUSE TOFF AT T
      RETURN
6     CREATE LAND
      STORE K IN RWAY(LAND)
      CAUSE LAND AT T
      RETURN
      END NXTOP
```

```
      FUNCTION FREER(K,I,FLT)
C     FREER CALCULATES THE FIRST TIME AT WHICH FLIGHT FLT CAN PERFORM
C     OPERATION I ON RUNWAY K WITHOUT VIOLATING SEPARATION RULES.
      DIMENSION TR(25)
      LET J=0
       LET T=TIME
      IF TIN(FLT) GT T, LET T=TIN(FLT)
      LET M=TYPE(FLT)
      LET FREER=T
      IF I EQ 2, GO TO 4
      IF ERTI(K) IS EMPTY, RETURN
C     ERTI(K) IS THE SET OF 'TIEUPS' FOR THE END OF THE RUNWAY K.
C     A TIEUP IS A TIME INTERVAL DURING WHICH NO TAKEOFF MAY OCCUPY
C     THE END OF THE RUNWAY DUE TO INTERFERENCE FROM OTHER AIRCRAFT.
      LET TEM=TDMIN(K)
C     TDMIN IS A TIME LAG INTRODUCED INTO THE SCHEDULE OF A TAKEOFF
C     CORRESPONDING TO THE TIME IT TAKES A LANDING TO FLY FROM THE
C     OUTER MARKER TO TOUCHDOWN.  IT MAY BE LOOSELY THOUGHT OF AS
C     TAXIING TIME.
      DO TO 3,FOR EACH TIEUP IN ERTI(K)
      LET TT=TMAX(TIEUP)-TEM
C     THE END OF THE TIEUP, I.E. THE TIME WHEN THE END OF THE RUNWAY
C     BECOMES FREE, IS DISPLACED BACKWARDS TO GIVE THE TIME WHEN
C     THE TAKEOFF MAY BEGIN TAXI.
      IF TT LS T , GO TO 3
      LET J=J+1
      LET TR(J)=TT
 3    LOOP
      GO TO 12
    4 IF OMTI(K) IS EMPTY, GO TO 8
C     OMTI IS THE SET OF TIEUPS FOR THE OUTER MARKER.
      DO TO 5, FOR EACH TIEUP IN OMTI(K)
      LET TT=TMAX(TIEUP)
      IF TT LS T , GO TO 5
      LET J=J+1
      LET TR(J)=TT
 5    LOOP
    8 IF THTI(K) IS EMPTY, GO TO 12
      LET TEM=DOM(K)/VLAND(M)
C     THTI IS THE SET OF TIEUPS FOR THE THRESHOLD OF THE RUNWAY.
      DO TO 9, FOR EACH TIEUP IN THTI(K)
C     THRESHOLD TIEUPS ARE DISPLACED BACKWARDS TO GIVE THE TIME THAT
C     THE LANDING MAY PASS THE OUTER MARKER.
      LET TT=TMAX(TIEUP)-TEM
      IF TT LS T , GO TO 9
      LET J=J+1
      LET TR(J)=TT
 9    LOOP
```

```
 12     IF J EQ 0, RETURN
        LET FREER=TR(1)
        IF J EQ 1, RETURN
C       FREER IS SET EQUAL TO THE END OF THE LATEST TIEUP, WHEN THERE IS
C       NO LONGER ANY INTERFERENCE.
        DO TO 21, FOR JJ=(1)(J)
        IF TR(JJ) GT FREER, LET FREER=TR(JJ)
 21     LOOP
        RETURN
        END FREER
```

```
      ENDOGENOUS EVENT LAND
C     LAND CREATES ALL THE 'TIEUPS' WHICH
C     RESULT FROM AN AIRCRAFT LANDING.
      STORE RWAY(LAND) IN K
      IF Q(K,2) IS NOT EMPTY, GO TO 9
      WRITE ON TAPE 6, TIME,K
      FORMAT (' AT TIME',M3.2.2,S2,'LANDING QUEUE FOR RUNWAY',I3,S2,
     1  'IS EMPTY')
      STOP
 9
C     FIND THE LANDING TO BE 'SCHEDULED' AND STORE ITS ATTRIBUTES.
      REMOVE FIRST FLT FROM Q(K,2)
      STORE FLT IN FL
      LET M=TYPE(FL)
      LET V=VLAND(M)
      LET T = FRFER(K,2,FL)
      LET TD=T+DOM(K)/V
C     TIE UP THRESHOLD TO LANDING AIRCRAFT FROM TOUCHDOWN TIME UNTIL
C     AFTER RUNWAY OCCUPANCY TIME HAS ELAPSED.
      CREATE TIEUP
      LET TMIN(TIEUP)=TD
      LET TMAX(TIEUP)=TD+ROTL(M)
      FILE TIEUP IN THTI(K)
      CREATE FTIUP
      STORE K   IN RWAY(FTIUP)
      STORE 2 IN PT(FTIUP)
      CAUSE FTIUP AT TMAX(TIEUP)
C     TIE UP END OF RUNWAY TO DEPARTING AIRCRAFT FROM TOUCHDOWN UNTIL
C     AFTER RUNWAY OCCUPANCY TIME HAS ELAPSED.
      CREATE TIEUP
      LET TMIN(TIEUP)=TD
      LET TMAX(TIEUP)=TD+ROTL(M)
      FILE TIEUP IN ERTI(K)
      CREATE FTIUP
      STORE K   IN RWAY(FTIUP)
      STORE 3 IN PT(FTIUP)
      CAUSE FTIUP AT TMAX(TIEUP)
C     FIND THE FOLLOWING PLANE IN THE LANDING QUEUE
C     AND STORE ITS ATTRIBUTES.
      FIND FIRST, FOR EACH FLT IN Q(K,2),IF NONE, GO TO 11
      STORE FLT IN F
      LET MM=TYPE(F)
      LET S=VLAND(MM)
C     CREATE A TIEUP WHICH WILL MAINTAIN PROPER RADAR SEPARATION
C     BETWEEN ARRIVING AIRCRAFT.
      CREATE TIEUP
```

```
      IF S GE V, GO TO 20
C     IF THE LANDING SPEED OF THE PLANE BEING 'SCHEDULED' IS GREATER
C     THAN THAT OF THE FOLLOWING PLANE, TIE UP THE OUTER MARKER FROM
C     THE TIME THE FIRST PLANE PASSES THE OUTER MARKER UNTIL
C     THE TIME IT TAKES THE SECOND TO FLY THE SEPARATION DISTANCE
C     HAS ELAPSED.
      LET TMIN(TIEUP)=T
      LET TMAX(TIEUP)=T+SEPLL(M,MM)/S
      FILE TIEUP IN OMTI(K)
      CREATE FTIUP
      STORE K  IN RWAY(FTIUP)
      STORE 1  IN PT(FTIUP)
      CAUSE FTIUP AT TMAX(TIEUP)
      GO TO 11
C     IF THE LANDING SPEED OF THE FOLLOWING PLANE IS GREATER, TIE UP
C     THE THRESHOLD FROM TOUCHDOWN OF THE FIRST UNTIL THE TIME IT TAKES
C     THE SECOND TO FLY THE SEPARATION DISTANCE HAS ELAPSED.
   20 LET TMIN(TIEUP) = TD
      LET TMAX(TIEUP)=TD+SEPLL(M,MM)/S
      FILE TIEUP IN THTI(K)
      CREATE FTIUP
      STORE K  IN RWAY(FTIUP)
      STORE 2 IN PT(FTIUP)
      CAUSE FTIUP AT TMAX(TIEUP)
  11  IF OPER(K) LT 3, GO TO 2
C     CREATE A TIEUP WHICH WILL MAINTAIN PROPER SEPARATION BETWEEN
C     THIS LANDING AND A TAKEOFF ON THE SAME RUNWAY.
      CREATE TIEUP
      LET TMAX(TIEUP)=TD
      IF DME(M) GT 0, GO TO 1
C     IF THE LANDING HAS NO DISTANCE MEASURING EQUIPMENT, TIE UP THE
C     END OF RUNWAY TO DEPARTURES FROM THE TIME THE LANDING PASSES THE
C     D/A FIX UNTIL TOUCHDOWN.
      LET TMIN(TIEUP)=T+(DOM(K)-DAFIX)/V
      GO TO 101
C     IF THE LANDING HAS DME, FIND THE TAKEOFF SPEED OF THE
C     DEPARTURE AND COMPUTE THE TIEUP NECESSARY TO MAINTAIN SEPARATION.
 1     FIND FIRST, FOR EACH FLT IN Q(K,1), IF NONE, GO TO 2
      STORE FLT IN F
      LET MM=TYPE(F)
      LET S=VTOFF(MM)
      LET TMIN(TIEUP)=T+(DOM(K)-(SEPTL+.5*V**2/S*ROTT(MM)))/V
  101 FILE TIEUP IN ERTI(K)
      CREATE FTIUP
      STORE K  IN RWAY(FTIUP)
      STORE 3 IN PT(FTIUP)
      CAUSE FTIUP AT TMAX(TIEUP)
 2    IF NPT(K)  EQ 0, GO TO 10
```

```
C       NOW CREATE TIEUPS ON OTHER RUNWAYS, IF SUCH INTERFERENCE EXISTS.
        DO TO 8,FOR J=(1)(NPT(K))
        CREATE TIEUP
C       KK IS THE RUNWAY AFFECTED.
        LET KK=RPT(K,J)
C       IT IS THE TYPE OF TIEUP TO BE CREATED.
C       TIEUP TYPES 1, 2, AND 6 APPLY TO LANDINGS.
        LET IT=TPT(K,J)
        GO TO (3,4,6,6,6,5),IT
C       CREATE A TIEUP TO MAINTAIN INTER-ARRIVAL SEPARATION.
      3 FIND FIRST, FOR EACH FLT IN Q(KK,2), IF NONE, GO TO 6
        STORE FLT IN F
        LET MM=TYPE(F)
        LET S=VLAND(MM)
        IF S GE V, GO TO 325
        LET TMIN(TIEUP)=T
        LET TMAX(TIEUP)=T+SEPLL(M,MM)/S
        LET JJ=1
        GO TO 7
    325 LET TMIN(TIEUP)=TD
        LET TMAX(TIEUP)=TD+SEPLL(M,MM)/S
        LET JJ=2
        GO TO 7
C       CREATE A TIEUP TO MAINTAIN DEP/ARR SEPARATION.
      4 LET TMAX(TIEUP)=TD
        IF DME(M) GT 0, GO TO 425
        LET TMIN(TIEUP)=T+(DOM(K)-DAFIX)/V
        GO TO 450
    425 FIND FIRST , FOR EACH FLT IN Q(KK,1), IF NONE GO TO 6
        STORE FLT IN F
        LET MM=TYPE(F)
        LET S=VTOFF(MM)
        LET TMIN(TIEUP)=T+(DOM(K)-(SEPTL+.5*V**2/S*ROTT(MM)))/V
    450 LET JJ=3
        GO TO 7
C       TIE UP THE END OF AN INTERSECTING RUNWAY TO TAKEOFFS AND LANDINGS
C       UNTIL AFTER THE LANDING  PASSES THE INTERSECTION.
      5 LET TMIN (TIEUP) =TD
        LET A=(VTAXI-V)/ROTL(M)
        LET TEM=.5*A*ROTL(M)**2+V*ROTL(M)
C       IF THE LANDING WILL NOT REACH THE INTERSECTION,
C       TIE UP UNTIL THE LANDING TURNS OFF.
        IF TEM LE DINT(K,KK), GO TO 51
        LET B=V**2+2.*A*DINT(K,KK)
        LET TUP=TD+(-V+SQRT(B))/A
        GO TO 52
```

```
 51    LET TUP=TD+ROTL(M)
 52    LET TMAX(TIEUP)=TUP
       FILE TIEUP IN THTI(KK)
       CREATE FTIUP
       STORE KK IN RWAY(FTIUP)
       STORE 2 IN PT(FTIUP)
       CAUSE FTIUP AT TMAX(TIEUP)
       CREATE TIEUP
       LET TMIN(TIEUP)=TD
       LET TMAX(TIEUP)=TUP
       LET JJ=3
       GO TO 7
     6 DESTROY TIEUP
       GO TO 8
     7 GO TO(701,702,703),JJ
   701 FILE TIEUP IN OMTI(KK)
       GO TO 705
   702 FILE TIEUP IN THTI(KK)
       GO TO 705
   703 FILE TIEUP IN FRTI(KK)
   705 CREATE FTIUP
       STORE KK IN RWAY(FTIUP)
       STORE JJ IN PT(FTIUP)
       CAUSE FTIUP AT TMAX(TIEUP)
 8     LOOP
 10    CREATE NXTOP
       STORE K IN RWAY(NXTOP)
       LET NEXT(K)=0
       CAUSE NXTOP AT T
C      DTEM IS THE DELAY ENCOUNTERED BY THIS LANDING.
       LET DTEM=(T-TIN(FL))*60.
       IF TD LS TREG,GO TO 50
       CREATE PRINT
C      STORE DATA TO BE RECORDED AT TOUCHDOWN.
       STORE DTEM IN DLAY(PRINT)
       STORE K IN RWAY(PRINT)
       STORE 2 IN OP(PRINT)
       CAUSE PRINT AT TD
 50    DESTROY FLT CALLED FL
       LET LAST(K)=LAST(K)+1
       DESTROY LAND
       RETURN
       END LAND
```

```
      ENDOGENOUS EVENT TOFF
C     TOFF CREATES THE TIEUPS RESULTING FROM AN AIRCRAFT TAKING OFF.
      STORE RWAY(TOFF) IN K
      DESTROY TOFF
      IF Q(K,1) IS EMPTY, GO TO 16
C     FIND TAKEOFF TO BE SCHEDULED AND STORE ITS ATTRIBUTES.
      REMOVE FIRST FLT FROM Q(K,1)
      STORE FLT IN FL
      LET M=TYPE(FL)
      LET V=VTOFF(M)
      LET T=FREER(K,1,FL)
      LET TD=T+TDMIN(K)
C     TIE UP THE RUNWAY TO TAKEOFFS AND LANDINGS FOR DURATION OF THE
C     RUNWAY OCCUPANCY TIME.
      CREATE TIEUP
      LET TMIN(TIEUP)=TD
      LET TMAX(TIEUP)=TD+ROTT(M)
      FILE TIEUP IN THTI(K)
      CREATE FTIUP
      STORE K  IN RWAY(FTIUP)
      STORE 2 IN PT(FTIUP)
      CAUSE FTIUP AT TMAX(TIEUP)
      CREATE TIEUP
      LET TMIN(TIEUP)=TD
      LET TMAX(TIEUP)=TD+ROTT(M)
      FILE TIEUP IN ERTI(K)
      CREATE FTIUP
      STORE K  IN RWAY(FTIUP)
      STORE 3 IN PT(FTIUP)
      CAUSE FTIUP AT TMAX(TIEUP)
      FIND FIRST, FOR EACH FLT IN Q(K,1), IF NONE, GO TO 2
      STORE FLT IN F
      LET MM=TYPE(F)
C     TIE UP THE END OF THE RUNWAY TO THE NEXT TAKEOFF LONG ENOUGH
C     TO MAINTAIN INTER-DEPARTURE SEPARATION. THIS DEPENDS ON THE
C     TYPES OF THE TWO AIRCRAFT.
      CREATE TIEUP
      LET TMIN(TIEUP)=TD
      LET TMAX(TIEUP)=TD+SEPTT(M,MM)
      FILE TIEUP IN ERTI(K)
      CREATE FTIUP
      STORE K  IN RWAY(FTIUP)
      STORE 3 IN PT(FTIUP)
      CAUSE FTIUP AT TMAX(TIEUP)
    2 IF OPER(K) LT 3, GO TO 5
      FIND FIRST, FOR EACH FLT IN Q(K,2), IF NONE, GO TO 5
      STORE FLT IN F
      LET S=VLAND(TYPE(F))
```

```
C       CREATE A TIEUP TO MAINTAIN DEP/ARR SEPARATION.
        CREATE TIEUP
        LET TMIN(TIEUP)=TD
        IF DME(TYPE(F)) EQ 0, GO TO 3
        LET TMAX(TIEUP)=TD+(SEPTL+.5*S**2/V*ROTT(M))/S
        GO TO 4
 3      LET TMAX(TIEUP)=TD+DAFIX/S
    4   FILE TIEUP IN THTI(K)
        CREATE FTIUP
        STORE K IN RWAY(FTIUP)
        STORE 2 IN PT(FTIUP)
        CAUSE FTIUP AT TMAX(TIEUP)
 5      IF NPT(K)  EQ 0, GO TO 15
C       CREATE TIEUPS OF OTHER RUNWAYS AS REQUIRED.
        DO TO 14,FOR J=(1)(NPT(K))
        CREATE TIEUP
C       KK - RUNWAY AFFECTED
        LET KK=RPT(K,J)
C       IT - TYPE OF TIEUP
C       ONLY TYPES 3, 4, 5, AND 6 APPLY TO TAKEOFFS.
        LET IT=TPT(K,J)
        GO TO(12,12,6,8,8,10),IT
C       CREATE A TIEUP TO MAINTAIN PROPER DEP/ARR SEPARATION.
      6 FIND FIRST,FOR EACH FLT IN Q(KK,2), IF NONE,GO TO 12
        STORE FLT IN F
        LET MM=TYPE(F)
        LET S=VLAND(MM)
        LET TMIN(TIEUP)=TD
        LET JJ=2
        IF DME(TYPE(F)) EQ 0, GO TO 7
        LET TMAX(TIEUP)=TD+(SEPTL+.5*S**2/V*ROTT(M))/S
        GO TO 13
      7 LET TMAX(TIEUP)=TD + DAFIX/S
        GO TO 13
      8 FIND FIRST,FOR EACH FLT IN Q(KK,1), IF NONE, GO TO 12
        STORE FLT IN F
        LET MM=TYPE(F)
C       CREATE A TIEUP TO MAINTAIN PROPER INTER-DEPARTURE SEPARATION.
        LET TMIN(TIEUP)=TD
C       IF THE RUNWAYS ARE DEPENDENT, USE THE SAME SEPARATION AS FOR ONE
C       RUNWAY, I.E. THOSE IN THE SEPTT ARRAY.
        LET TMAX(TIEUP)=TD+SEPTT(M,MM)
C       IF THE RUNWAYS ALLOW SIMULTANEOUS DEPARTURES WHEN THEY DIVERGE,
C       USE THE SEPARATIONS IN THE SEP2 ARRAY.
        IF IT EQ 5,LET TMAX(TIEUP)=TD+SEP2(M,MM)
        LET JJ=3
        GO TO 13
C       TIE UP THE END OF AN INTERSECTING RUNWAY TO ALL OPERATIONS UNTIL
C       THE TAKEOFF PASSES THE INTERSECTION.
```

```
 10     LET TMIN(TIEUP)=TD
        LET A =V/ROTT(M)
        LET TEM=.5*A*ROTT(M)**2+V*ROTT(M)
C       IF THE TAKEOFF IS AIRBORNE BEFORE REACHING THE INTERSECTION,
C       TIE UP ONLY UNTIL AIRBORNE.
        IF TEM LE DINT(K,KK), GO TO 51
        LET B=V**2+2.*A*DINT(K,KK)
        LET TUP=TD+(-V+SQRT(B))/A
        GO TO 52
 51     LET TUP=TD+ROTT(M)
 52     LET TMAX(TIEUP)=TUP
        FILE TIEUP IN THTI(KK)
        CREATE FTIUP
        STORE KK IN RWAY(FTIUP)
        STORE 2 IN PT(FTIUP)
        CAUSE FTIUP AT TMAX(TIEUP)
        CREATE TIEUP
        LET TMIN(TIEUP) =TD
        LET TMAX(TIEUP)=TUP
        LET JJ=3
        GO TO 13
    12 DESTROY TIEUP
        GO TO 14
    13 GO TO(14,131,132),JJ
   131 FILE TIEUP IN THTI(KK)
        GO TO 135
   132 FILE TIEUP IN FRTI(KK)
   135 CREATE FTIUP
        STORE KK IN RWAY(FTIUP)
        STORE JJ IN PT(FTIUP)
        CAUSE FTIUP AT TMAX(TIEUP)
    14 LOOP
 15      CREATE NXTOP
        STORE K IN RWAY(NXTOP)
        LET NEXT(K)=0
        CAUSE NXTOP AT T
C       DTEM - THE DELAY INCURRED BY THIS TAKEOFF
        LET DTEM=(TD-TDMIN(K)-TIN(FL))*60.
        IF TD LS TREG,GO TO 50
        CREATE PRINT
C       STORE DATA TO BE RECORDED AT THE TIME THE TAKEOFF TURNS
C       ON TO THE RUNWAY.
        STORE DTEM IN DLAY(PRINT)
        STORE K IN RWAY(PRINT)
        STORE 1 IN OP(PRINT)
        CAUSE PRINT AT TD
 50     DESTROY FLT CALLED FL
        LET LAST(K)=LAST(K)+1
        RETURN
 16      WRITE ON TAPE 6, TIME, K
        FORMAT (' AT TIME',D2.4,S2,'TAKEOFF QUEUE FOR RUNWAY',I3,S2,
      1   'IS EMPTY')
        STOP
        END TOFF
```

```
      ENDOGENOUS EVENT FTIUP
C     FTIUP REMOVES TIEUPS FROM THEIR SETS AND DESTROYS THEM WHEN
C     SIMULATED TIME PASSES THE END-LIMIT OF THE TIEUP.
      STORE RWAY(FTIUP) IN K
      STORE PT(FTIUP) IN J
      DESTROY FTIUP
      GO TO(10,20,30),J
   10 REMOVE FIRST TIEUP FROM OMTI(K)
      GO TO 40
   20 REMOVE FIRST TIEUP FROM THTI(K)
      GO TO 40
   30 REMOVE FIRST TIEUP FROM FRTI(K)
   40 DESTROY TIEUP
      RETURN
      END FTIUP
```

```
      ENDOGENOUS EVENT CHOUR
      LET IHOUR=IHOUR+1
      IF IHOUR GT NH, LET IHOUR=1
      LET T=TIME+1.
      IF T LE TEND, CAUSE CHOUR AT T
      DO TO 1, FOR EACH O I
      STORE GENN(I) IN GEN
      CANCEL GEN
      CALL RNG(**INITR,*R,1,0)
      CAUSE GEN AT TIME-LAMBD(I,IHOUR)*ALOG(1.-R)
1     LOOP
      IF TIME LE TBEG, RETURN
      LET II=IHOUR-1
      DO TO 4, FOR EACH RW K
      LET NOPS=HNRW(K,1)+HNRW(K,2)
      DO TO 12, FOR EACH O I
      LET TNRW(K,I)=TNRW(K,I)+HNRW(K,I)
12     LOOP
      IF CAP GT 0, GO TO 11
      IF K GT 1, GO TO 20
      WRITE ON TAPE 6, II,K,HNRW(K,2),HNRW(K,1),NOPS
      FORMAT (I4,I6,S4,3I9)
      GO TO 22
20    WRITE ON TAPE 6,     K,HNRW(K,2),HNRW(K,1),NOPS
      FORMAT (S4,I6,S4,3I9)
      GO TO 22
11    LET TDEL=0.
      DO TO 2, FOR EACH O I
      LET TDRW(K,I)=TDRW(K,I)+HDRW(K,I)
      LET TDEL=TDEL+HDRW(K,I)
2     LOOP
      LET B1=HNRW(K,1)
      IF B1 GT 0., GO TO 5
      LET D1=0.
      GO TO 6
5     LET D1=HDRW(K,1)/B1
6     LET B2=HNRW(K,2)
      IF B2 GT 0.,GO TO 7
      LET D2=0.
      GO TO 8
7     LET D2=HDRW(K,2)/B2
8     LET B3=NOPS
      IF B3 GT 0., GO TO 9
      LET D3=0.
      GO TO 10
9     LET D3=TDEL/B3
```

```
10    IF K GT 1, GO TO 21
      WRITE ON TAPE 6, II,K,HNRW(K,2),HNRW(K,1),NOPS,D2,D1,D3
      FORMAT (I4,I6,S4,3I9,S3,3D7.1)
      GO TO 22
21    WRITE ON TAPE 6,     K,HNRW(K,2),HNRW(K,1),NOPS,D2,D1,D3
      FORMAT (S4,I6,S4,3I9,S3,3D7.1)
22    DO TO 3, FOR EACH O I
      LET HDRW(K,I)=0.
      LET HNRW(K,I)=0
3     LOOP
4     LOOP
      RETURN
      END CHOUR
```

```
      ENDOGENOUS EVENT PRINT
C     PRINT  RECORDS DATA ON EACH FLIGHT AT THE TIME IT ACTUALLY
C     TOUCHES DOWN OR TURNS ON TO THE RUNWAY, AS THE CASE MAY BE.
      STORE RWAY(PRINT) IN K
      STORE DLAY(PRINT) IN D
      STORE OP(PRINT) IN I
      DESTROY PRINT
      LET HDRW(K,I)=HDRW(K,I)+D
      LET HNRW(K,I)=HNRW(K,I)+1
C     NTOFF AND NLAND ARE THE TOTAL NUMBER OF TAKEOFFS AND LANDINGS
C     DURING THIS HOUR.
C     DELT AND DELL ACCUMULATE TOTAL DELAY ON TAKEOFFS AND
C     LANDINGS BY HOUR.
      GO TO(10,20),I
   10 LET NTOFF(IHOUR)=NTOFF(IHOUR)+1
      LET DELT(IHOUR)=DELT(IHOUR)+D
      RETURN
   20 LET NLAND(IHOUR)=NLAND(IHOUR)+1
      LET DELL(IHOUR)=DELL(IHOUR)+D
      RETURN
      END PRINT
```

```
      ENDOGENOUS EVENT ENDS
      WRITE ON TAPE 6, INITR
      FORMAT ('0'//'0FINAL RANDOM NUMBER SEED ',O12)
      WRITE ON TAPE 6
      FORMAT ('1SUMMARY REPORT FOR THIS RUN'//)
      WRITE ON TAPE 6
      FORMAT (S5,'TOTAL THROUGHPUT'//
     1 S8,'RUNWAY',S8,'OPERATIONS PERFORMED'/S19,'LANDINGS  TAKEOFFS',
     2 S4,'TOTAL'/)
      LET MLAND=0
      LET MTOFF=0
      DO TO 1, FOR EACH RW K
      LET MLAND=MLAND+TNRW(K,2)
      LET MTOFF=MTOFF+TNRW(K,1)
      LET NOPS=TNRW(K,2)+TNRW(K,1)
      WRITE ON TAPE 6, K,TNRW(K,2),TNRW(K,1),NOPS
      FORMAT (S10,I1,S4,3I10)
1     LOOP
      LET NOPS=MLAND+MTOFF
      WRITE ON TAPE 6, MLAND,MTOFF,NOPS
      FORMAT (S9,'TOTAL ',3I10///)
      WRITE ON TAPE 6
      FORMAT (S5,'AVERAGE HOURLY THROUGHPUT'//
     1 S8,'RUNWAY',S8,'OPERATIONS PERFORMED'/S19,'LANDINGS  TAKEOFFS',
     2 S4,'TOTAL'/)
      LET THR=TEND-TBEG
      LET TLAND=0.
      LET TTOFF=0.
      DO TO 2, FOR EACH RW K
      LET T1=TNRW(K,1)
      LET TTOFF=TTOFF+T1
      LET T1=T1/THR
      LET T2=TNRW(K,2)
      LET TLAND=TLAND+T2
      LET T2=T2/THR
      LET T=TNRW(K,1)+TNRW(K,2)
      LET T=T/THR
      WRITE ON TAPE 6, K,T2,T1,T
      FORMAT (S10,I1,S4,3D8.1)
2     LOOP
      LET T=(TLAND+TTOFF)/THR
      LET TLAND=TLAND/THR
      LET TTOFF=TTOFF/THR
      WRITE ON TAPE 6, TLAND,TTOFF,T
      FORMAT (S9,'TOTAL',S1,3D8.1///)
```

```
      IF CAP LE 0, GO TO 4
      WRITE ON TAPE 6
      FORMAT (S5,'AVERAGE HOURLY DELAY'//
     1  S8,'RUNWAY',S11,'DELAY (MINUTES)'/S19,'LANDINGS  TAKEOFFS',S4,
     2  'TOTAL'/)
      LET DLAND=0.
      LET DTOFF=0.
      DO TO 3, FOR EACH RW K
      LET T1=TDRW(K,1)
      LET DTOFF=DTOFF+T1
      LET T1=T1/THR
      LET T2=TDRW(K,2)
      LET DLAND=DLAND+T2
      LET T2=T2/THR
      LET T=TDRW(K,1)+TDRW(K,2)
      LET T=T/THR
      WRITE ON TAPE 6, K,T2,T1,T
      FORMAT (S10,I1,S4,3D8.1)
3     LOOP
      LET T=(DLAND+DTOFF)/THR
      LET DLAND=DLAND/THR
      LET DTOFF=DTOFF/THR
      WRITE ON TAPE 6, DLAND,DTOFF,T
      FORMAT (S9,'TOTAL',S1,3D8.1///)
4     STOP
      END ENDS
```


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