A PROCEDURE FOR AIRPORT SYSTEMS ANALYSIS EMPHASIZING COMPUTER SIMULATION

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Bachelor of Science

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West Point, New York

1962

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
MASTER OF ARCHITECTURAL ENGINEERING
May, 1968

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PREFACE

This thesis is concerned with developing a procedure for comprehensive airport systems analysis emphasizing digital computer simulation (GPSS). The basic airport traffic problem and its associated GPSS model are described and presented as a foundation for comprehensive simulation of complex airport systems. Traffic situations simulated include holding and approach operations for IFR, VFR and mixed IFR-VFR flight; runway, taxiway, and ramp operations; terminal service operations; and departure operations. Systems analysis of existing or proposed airport physical configurations and operating procedures is based on output data reflecting traffic delay, its associated costs, and efficiency at critical elements throughout the airport system.

I would like to take this opportunity to express my sincerest appreciation and gratitude for the assistance and guidance given me by the following persons:

Professor R. Bruce Miller, School of Architecture, who, as my faculty adviser, introduced me to the field of airport planning and provided the principal advice, encouragement and opportunity for comprehensive research that underlies this thesis.

Professor Frank F. Ehrenthal, School of Architecture, for his personal interest and encouragement in my work.

Dr. Mohamed Abdel-Hady and the members of his graduate seminar in Airport Planning and Design, School of Civil Engineering, for their interest in this work and for the benefits I derived from their knowledge of airport planning.

Dr. Robert L. Janes, School of Civil Engineering, for his interest in this work and for his instruction on matters concerning transportation systems planning and engineering.

Professor Frederick M. Black and the members of his class in GPSS programming, School of Business Administration, for their invaluable assistance in helping me to develop the programming capability required for this research.

Terry R. Gonderinger, School of Business Administration, whose statistical analysis and verification of GPSS as a reliable tool for systems simulation provided a vital service for my own research.

Major John R. DeSola, Captain John E. Lee and Captain Michael M. McMillan, all of the United States Air Force and the School of Industrial Engineering and Management, for their interest and advice concerning matters of Air Traffic Control procedure and GPSS programming.

Captain David S. Robinson, United States Air Force and the School of Mechanical Engineering, for his personal interest and advice in refining the Air Traffic Control logic implicit within the airport systems simulation procedure.

Mr. Irl D. Miller, Jr. and his staff in the Airport Training Section, Federal Aviation Administration Academy,

Will Rogers Airport, Oklahoma City, for their interest in this work and for the instruction they provided me in their airport planning course.

Miss Sarah S. Seemann and Mr. Donald K. Dean of International Business Machines Corporation, Oklahoma City, for their interest, encouragement and technical support in matters of GPSS programming.

Dr. Robert W. Simpson of the Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, for his personal interest and encouragement in this work and particularly for his generosity in providing me with material from his doctoral research: <u>An Analytical Investigation of Air Traffic Operations in the Terminal Area</u>. His research has provided the analytical base for much of my own simulation efforts.

The Air Force Institute of Technology for the financial support that provided the opportunity for me to pursue this research.

Lastly, I would like to express my appreciation to my wife, Pilar, for her typing and proof-reading assistance and for the understanding and encouragement which has been instrumental in the preparation of this thesis.

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NOMENCLATURE

A/B	airborne
A/C	aircraft
AD	arrival-departure pair
ARTC	Air Route Traffic Control
ATC	Air Traffic Control
AWTV	wing tip vortices caused by arrival aircraft
b	time required to fly the length of the base leg in the VFR trombone
c	time required to fly the length of the commitment-to-land interval (or minimum stabilization distance)
C1	current simulation clocktime (also C0, C2, C3)
CLI	commitment-to-land interval (also called clear-to-land interval)
CTO	clear-to-take-off interval
d	time required to fly the length of the common departure path
D	departure aircraft's separation requirement with respect to a landing aircraft
DOC	Direct Operating Cost
DW	downwind
DWTV	wing tip vortices caused by a departing aircraft
f	wind factor
FAA	Federal Aviation Administration (formerly, Federal Aviation Agency)
FIFO	first in, first out

FP	flight plan
G/A	general aviation
GCA	Ground Controlled Approach
GPSS	General Purpose Systems Simulator (also referred to as General Purpose Simulation System)
HRLY	hourly
IA	interarrival
ID	interdeparture
IFR	Instrument Flight Rules
ILS	Instrument Landing System
INT	intersection
LE	less than or equal to
m	time required to fly the length of the common approach path (after Blumstein)
MA	missed approach
MI	aircraft transit time
MP	intermediate transit time
N	aircraft landing sequence number
NAVAID	any navigation aid
NU	facility not in use
O/M	outer marker
OPN	operation
R	time required to fly the optimum path through the regulator
RW	time required for runway operation
RW(X)	runway operation time for a preceding aircraft
S_o	time required to fly the minimum distance separation requirement (after Blumstein)
SNF	storage space not full

STAT.	statistical
t_o	time required to fly the minimum time separation requirement (after Blumstein)
T & G	touch and go
TMA	terminal area
TW	taxiway
VFR	Visual Flight Rules
W	wait count or the number of aircraft in the VFR landing pattern
WX	weather
X(B)	the landing sequence number of the aircraft that has most recently turned onto final from the base leg

CHAPTER I

INTRODUCTION TO THE AIRPORT PROBLEM

In the ten years that have passed since the introduction of the jet transport, air travel has come to mean speed, convenience, reliability and even economy to much of the traveling public. However, today these assets of air travel are rapidly being diminished. While a dynamic aircraft technology has combined with an explosive growth in national wealth and an equally strong desire for increased public mobility to create an exponentially growing demand for air transportation, there has been a critical failure to provide the airport systems needed to support this transportation demand.

Today there exists severe traffic congestion both in the air and on the ground at major airports. To the air traveler this congestion results in delay which manifests itself in many forms of inconvenience and expense. To the airline this congestion and its resultant delay means increased operating costs, loss of revenue and severe scheduling problems. To the Air Traffic Controller this congestion means a greatly enhanced danger of mid-air collision. To the local community this congestion means increased noise, air pollution and crash hazard as well as less efficient transportation service.

At peak periods, such as during the Christmas season, major airports like Kennedy International in New York may have 400 or more aircraft operating in or near their terminal areas.[1] At such airports arriving aircraft must be stacked in holding patterns in the air around the airport while they wait for permission to land. Under normal conditions arriving aircraft have come to expect delays of 20 to 30 minutes before being allowed to land. At peak periods, however, there are so many aircraft in holding stacks around Kennedy that approaching aircraft are directed to stack hundreds of miles away before being allowed to join the stacks near the airport.[2] Arrival delays under these circumstances may amount to three or four hours. Many arriving flights, particularly international flights with low fuel reserves, are not able to absorb this amount of delay and are forced to find an alternate airport for landing. Such incidents create severe problems for both the air passengers and the airlines. On the ground as many as 80 aircraft, loaded and engines running, have been observed lined up along taxiways while waiting for departure clearance.[3] Such conditions have caused departure delays of as much as four hours. Even under normal conditions departure delay at Kennedy will amount to about 30 minutes. In addition, airliners are frequently delayed on ramps waiting for gate positions at the terminal to open. While the above mentioned delays are not usually fully realized by the traveling public (because of the comfort of modern airliner accommodations and the efficiency of airline hostesses), virtually every air traveler is aware of the congestion and delay found in most major terminals and their ground approaches.

Air travel is essentially a commercial activity and as such its status is determined primarily on an economic basis. The value of time, convenience and reliability are compared with the cost of providing air transportation. Consequently the cost of congestion and its resultant delay is a major factor in considering the airport problem. In 1965 U. S. airlines experienced over 330,000 hours of airport delay.[4] This delay has been estimated to have cost $64,000,000 in fuel, crew time and related charges.[5] (The cost quoted is referred to as Direct Operating Cost or DOC. R. J. Sutherland, Airport Engineer for American Airlines, has provided an indication of the total cost. The DOC for a Boeing 707 is approximately $900 per hour. The earning capacity of this aircraft is approximately $2,000 per hour. Depreciation on the aircraft is approximately $100 per hour. Therefore the total cost of an hour's delay to this aircraft is in the vicinity of $3,000.[6] Because of the difficulties involved in obtaining total cost data from the airlines, most airport planners have relied on DOC data rather than the total cost as reflected above. Consequently, much of the cost analysis in past and present airport planning has been based on grossly inadequate cost data.)

A further problem that must be appreciated is that delay appears to follow a growth curve which is exponential. Specifically, with each increase in traffic demand for airport service, the probability of delay increases at a greater rate. Figure 1 illustrates the exponential curve. This curve is extremely pertinent to many current socio-economic problems. Several of the socio-economic factors affecting air transportation (demand, delay, cost, need for new facilities, capacity, range, speed, and weight of new aircraft, etc.) may be partially described by this growth curve. It is becoming increasingly clear in dealing with problems reflecting this exponential growth curve that experience and progress made in the past is not a reliable measure of the rate at which things will happen in the future. For example: it has taken 15 years for traffic to experience an average delay of 20 minutes at Kennedy; yet, assuming that current trends persist, the average delay at Kennedy will increase by another 20 minutes within the next eighteen months alone.[7]

As inferred immediately above, the present airport problem is overshadowed by the prospect of virtual strangulation of the airport system in the coming decade. Senator Mike Monroney, Chairman of the United States Senate Subcommittee on Aviation, has recently reported that in the next decade there will be a 440% increase in airline travel, a 1370% increase in air cargo shipment and an increase in peak hour operations at major airports of about 200%.[8]

▨ Growth potential if current trends persist (all growth factors demonstrate exponential characteristics)

▥ Growth potential that can be satisfied by planning policies which rely on linear projections of past experience

▨ Growth potential that must either be stifled or satisfied by planning policies that fully appreciate the problems of exponential growth

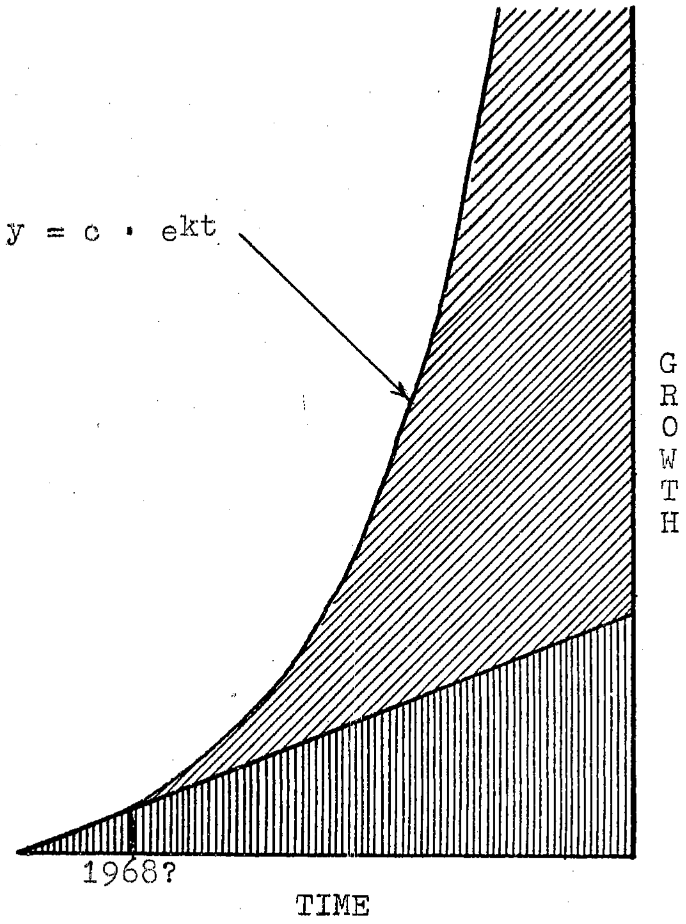


Figure 1. Exponential Growth Curve

To handle this traffic New York will have to double the terminal capacity of all three of its major airports, while Atlanta, for example, will need to develop six times its present terminal capacity.[9]

The seriousness of these estimates may be better appreciated in light of the fact that it presently takes from five to ten years to plan and develop a major airport. Yet there appears to be an immediate need for dozens of new or expanded airports many times the size of present airports. Tables I through IV represent conservative estimates of 1980 airport system demands and needs.

In view of the above mentioned factors Senator Monroney's subcommittee has defined the airport problem as consisting of two parts:[10]

(1) Current airport congestion, for which additional airport construction and development, even on a crash basis, is no solution. Solution to this problem is to come from better utilization of existing airports and from the construction of separate but fully equipped general aviation airports (which can be developed fairly quickly and economically).

(2) Future airport congestion, for which the solution is the construction of new airports and the improvement and expansion of existing airports to meet predicted traffic demand and aircraft technological changes expected in the next decade.

The objective of this thesis has been to develop a

TABLE I

NATIONAL ECONOMIC INDICATORS USED IN PREPARING THE NATIONAL AIRPORT PLAN, 1968-72

Economic Indicator	1965	1980
Population (millions)	194	235
Gross National Product (billions) . . .	614	1160
Air carrier passengers (millions) . . .	95	482
Aircraft operations FAA tower airports	35.6	184.6
Fuel consumption (billions of gallons).	4	17
Civil aircraft:		
Air carrier	2,125	3,600
General aviation	88,742	210,000
Aircraft production	11,050	33,500

Source: "The National Airport System," Interim Report of the Aviation Subcommittee to the Committee on Commerce, United States Senate, January, 1968, p. 4.

TABLE II

FORECAST OF AVIATION DEMAND AT 22 LARGE HUB AIRPORTS

Aviation demand	1965	1980
Aircraft operations (millions).	20.3	74.6
Enplaned passengers (millions).	69.5	370.6
Air cargo tons (millions)	1.3	19.7
General aviation aircraft (thousands) .	20.3	50.3

Source: "The National Airport System," Interim Report of the Aviation Subcommittee to the Committtee on Commerce, United States Senate, January, 1968, p. 4.

TABLE III

FORECAST OF SELECTED 1980 FACILITY NEEDS AT 22 LARGE HUB AIRPORTS

Facility	Expansion needs
Air carrier:	
Gate Positions	2,774
Vehicle parking area (square yards) . . .	11,500,000
Terminal building area (square feet). . .	52,300,000
Cargo building area (square fee).	7,900,000
Aircraft apron area (square yards). . . .	23,800,000
General aviation:	
Vehicle parking area (square yards) . . .	3,300,000
Terminal building space (square feet) . .	3,500,000
Aircraft apron area (square yards):	
Hanger area	22,100,000
Open area	45,300,000

Source: "The National Airport System," Interim Report of the Aviation Subcommittee to the Committee on Commerce, United States Senate, January, 1968, p. 4.

TABLE IV

ESTIMATED FUNDING REQUIREMENTS FOR DEVELOPMENT OF GENERAL AVIATION AIRPORTS

Purpose of expenditure	1969-78 est. reqts.	
	nbr. of units	millions of dollars
Construction of new "reliever" airports.	224	300
Other new airport construction . . .	680	210
Development of existing airports . .	2,324	345

Source: "The National Airport System," Interim Report of the Aviation Subcommittee to the Committee on Commerce, United States Senate, January, 1968, p. 5.

procedure which will allow comprehensive airport systems analysis on a practical basis. This procedure emphasizes use of digital computer simulation as an effective tool in the analysis of new airport systems or changes in existing systems. As such, this procedure is directly applicable to both parts of the airport problem as it has been defined above.

Chapter II discusses briefly: (1) the need for a systems approach to the airport problem, (2) previous analytical work in the fields of air traffic control and airport systems analysis, (3) the basic air traffic control system applied in the terminal area, (4) digital computer simulation, and (5) the basic airport system in terms of a GPSS model.

Chapter III presents a comprehensive computer simulation procedure for airport systems analysis. This presentation consists of a fully integrated series of flow diagrams reflecting the essential aspects of the terminal area air traffic control system. Cost/Benefit and Cost/Effectiveness analysis of the airport system is developed directly from the simulation procedure. A detailed narrative accompanies the flow diagrams.

Chapter IV discusses potential applications of the procedure described in Chapter III. Primary emphasis is placed on the basic philosophy to be developed in applying the simulation procedure to specific airport problems.

Chapter V briefly summarizes the main text and offers proposals for continued research into the airport problem utilizing the concepts of systems analysis and computer simulation.

Appendices A and B provide a more thorough discussion of subject areas referred to in the main text; specifically: Terminal Area Air Traffic Control Procedures (Appendix A) and General Purpose Systems Simulation (Appendix B).

The main text has been advanced on the assumption that the reader has a basic understanding of the material referenced in the appendices. If, however, this is not the case, it is recommended that the reader refer to the applicable appendices before continuing further in the main text.

FOOTNOTES

[1] "Controlling Air Traffic Coast to Coast", _Time_, March 27, 1967, p. 52.

[2] "Can Air Travel Be Kept Safe?" _U. S. News & World Report_, January 1, 1968, p. 55.

[3] Ibid.

[4] John Barbour, "Delays Haunt Airlines, Create Problems at Jammed Ports", _Tulsa Daily World_, December 2, 1967, p. 6.

[5] Ibid.

[6] B. J. Sutherland, as quoted in Discussion, Paul H. Stafford and Martin A. Warskow, "Airport Design By Economic Analysis", _Journal of the Air Transport Division_, _Proceedings of the American Society of Civil Engineers_, AT 2 (1961), p. 52.

[7] "Can Airports Cope With the Jet Age?" _Business Week_, July 22, 1967, p. 61.

[8] Benjamin M. Elson, "Systems Approach to Airport Snarl Urged", _Aviation Week & Space Technology_, January 15, 1968, p. 47.

[9] Ibid.

[10] Ibid.

CHAPTER II

INTRODUCTION TO AIRPORT SYSTEMS ANALYSIS

While the scope of this thesis is restricted to an understanding of the Terminal Area Air Traffic Control System as it effects airport planning, it is paramount that the airport be recognized as a key element in the total transportation system as well as a major element in the urban and regional environmental systems. The airport system is comprised of many complex components and each component of the system must be planned, developed and operated in a precise manner that allows it to serve and synchronize with all other components for optimum performance on the part of the total system. Solving the problems of one component without due regard for the remaining components usually only creates problems elsewhere in the system which in turn diminish or eliminate entirely the benefits of the solution initially sought. The complexity and magnitude of the airport problem is staggering; however, analytical and experimental methods and total systems concepts developed by the aerospace industry and the Department of Defense provide effective and ready tools for approaching this problem. Most importantly, the advent of systems analysis provides the airport planner with the opportunity to establish a foundation of knowledge based not upon the limited experience gained from the development of a particular system in the past but rather upon the broad experience gained from studying and working with systems in general.[1] This approach is stressed as a highly desirable alternative to the reliance on empirical methods currently found in airport planning.

Previous Analytical Work in the Fields of Traffic Control and Airport Systems Analysis

While there has been an enormous amount of highly sophisticated research into the problems of air traffic control, there seems to be a critical lack of truly comprehensive research into the problems of the airport from the planner's viewpoint. Airport planners have become increasingly aware of the need for a systems approach in airport planning. To date, however, most of their activity seems directed towards reinforcing established, though repeatedly inadequate, empirical methods rather than developing the ability to use the tools of systems analysis. At present the most productive activity in the field of airport planning is being generated by members of the systems-oriented airline and aerospace industries. There has recently been an encouraging tendency for airport planners to collaborate with these systems specialists. A second source of valid analytical data is the research oriented university. The theoretical and analytical base for most of this thesis is founded on the research of R. W. Simpson of the Department of Aeronautics and Astronautics, Massachusetts Institute of Technology; R. Horonjeff and R. Oliver of the Institute of Transportation and Traffic Engineering, University of California; and T. Rallis of the Technical University of Denmark. Their research has investigated each element of the airport system, primarily for the purpose of understanding and evaluating the operation of the Terminal Area Air Traffic Control System. (The exception being Rallis, who was primarily concerned with defining the total systems character of the airport from a planning viewpoint.) However, it is not apparent from current publications that any of the above researchers have developed a capability for describing and studying the airport as a total system. While this capability may be unnecessary in pure research, it is virtually essential to any analytical procedure applied in the field due to the critical need to know as precisely as possible how a change in one particular component effects all other components of the system. It is toward this capability that the procedure described in Chapter III is directed.

The Terminal Area Air Traffic Control System

Normally the airport is considered as a two-dimensional facility; however, it has a third (as well as a fourth when time is considered) dimension which is perhaps its most critical. As a four-dimensional facility the airport will be hereafter referred to as the terminal area. The terminal area defines a zone within which some form of control is exercised over all aircraft movement. The boundary of this area varies but it is usually determined by a radius of 25-50 miles from the center of the airport. Aircraft outside the terminal area are assumed to move radially through airways toward the terminal area, arriving at the boundary from random directions at random times. Arrival aircraft make their final approach to the airport from a direction determined primarily by wind conditions. For safety reasons it is necessary to establish a minimum separation between aircraft. The interval between successive landings is dictated by a required space separation before entering the common landing path, and by a required time separation at the threshold of the runway. A similar minimum time interval must be maintained between successive departures. Departures are interposed between landing aircraft whenever possible; however, priority is given to the landing aircraft. Consequently, a departure can only be authorized in front of a landing aircraft if the take-off can be executed before the landing aircraft reaches a prescribed minimum distance from the runway; otherwise, the departure aircraft must wait until the landing aircraft has cleared the runway. Thus the Terminal Area Air Traffic Control process is primarily one that: (1) transforms random arrivals into an orderly flow for landing and (2) maintains a prescribed minimum separation between aircraft.

Digital Computer Simulation

Initial research into the airport problem involved the use of mathematical models, particularly those reflecting the principles of queuing theory. This method of analysis has been a powerful tool in the hands of the systems analyst. However, the mathematical model has two limitations which greatly restrict its use in airport systems analysis: (1) the mathematical model reflects a generalized statement of a basic problem (it is severely limited in the analysis of a specific problem of any complexity) and (2) when the model begins to reflect any degree of sophistication, the mathematical derivations become extremely difficult to work with. Many of the problems arising from the use of current airport planning methods result from reliance on over-simplified mathematical models. A current example is found in a primary airport planning reference which develops its analytical base on the assumption that aircraft arrive randomly at the runway. However, as stated previously, a major role of the Air Traffic Control System is to derandomize arriving aircraft before they enter the common final approach path. Thus, there is in actuality, a very carefully regulated flow of landing aircraft at the runway. Such faulty assumptions usually are corrected by empirical means and consequently the method becomes essentially empirical rather than analytical. As mentioned previously, empirical methods (based primarily on past performance) have not been very adaptive to the problems of dynamic systems such as the airport.

In order to study a problem of the complexity found in the airport system it is necessary to construct an investigative model of the system. The construction and operation of this model is called simulation and forms the experimental counterpart of mathematical methods of analysis.[2] In contrast to the mathematical model, the simulation model provides a capability for describing and investigating a specific systems problem in whatever detail needed to give required results. The introduction of the digital computer and the general purpose systems simulation language (GPSS, SIMSCRIPT, etc.) has provided the airport systems analyst a capability for defining and studying virtually any type of airport problem at a level of detail never before realized.

GPSS is a computer language based on a set of macro-level instructions. Each of these instructions refers to a block in a flow diagram that describes the system being simulated. A family of block types has been established to allow the modeling and simulation of virtually any type of system (though GPSS works most efficiently with models in which the time factor is related to other attributes of the system; i.e., queueing models). GPSS can be visualized as consisting of a stationary block diagram imprinted into the computer memory with the program acting to move entities (aircraft) through this flow diagram in relation to a real-time clock (that has been greatly speeded up in the computer model).[3] Pertinent statistics reflecting system performance are automatically as well as selectively collected and tabulated as output. Because of its flow diagram logic and method of model construction, GPSS is a very easy programming language to learn. Thus an airport systems analyst has only to devote a very minimum amount of time to learning the techniques of computer programming; consequently, he has most of his time available for studying the airport problem. (Many planners and analysts today are trying to rely on programming specialists to solve their simulation problems; however, these people can only be effective if they are thoroughly familiar with the system to be modeled. This entails having a sophisticated understanding of the airport problem. The assumption of this author is that it is faster and more effective to have the planner or analyst learn programming than to have the programming specialist try to master the airport problem. However, once the planner or analyst has constructed the flow diagram for the model he feels meets the needs of his investigation, he should utilize the programming specialist for the purpose of refining the model in terms of programming sophistication. In any case there must always be a well-established communication between the two specialists.)

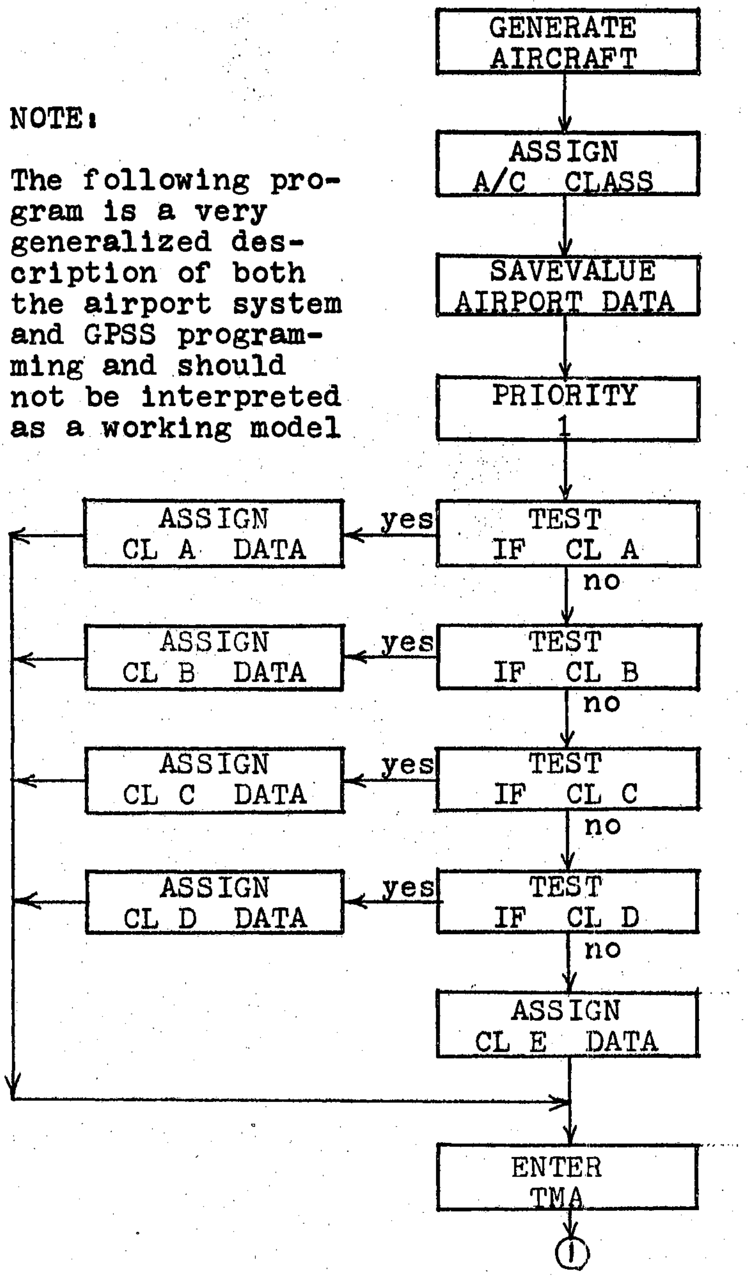
Figure 2 (p.22) is a very generalized description of the airport system in terms of a GPSS model. This simulation model is offered simply as an introduction to the more comprehensive modeling procedures presented in Chapter III. The analytical capability of this introductory model is roughly comparable to the optimum model that can be obtained from mathematical techniques. Neither the following model nor those to follow in Chapter III should be considered master models to be used directly in solving a specific problem. They are intended to illustrate how the logic of systems analysis can be constructed in a computer simulation model for the purpose of investigating a specific airport systems problem.

The GPSS language is extremely dynamic and in an attempt to keep it dynamic, its developers have updated its capability whenever possible. A minor problem arises from this fact in that the programmer must continuously update his knowledge of the language. The models in this thesis are written specifically for GPSS III (IBM 7040 computer) but the author has been exposed to the changes made for GPSS IV (IBM 360) and feels that there is no basic conflict in logic between GPSS III and GPSS IV. It is pertinent to realize, however, that computer languages will continue to grow dynamically and that the programmer should not become over-reliant on a specific programming technique but rather he should try to establish a programming logic that can be easily carried from one stage of computer language development to the next.

GPSS FLOW DIAGRAM FOR
AIRPORT SYSTEMS ANALYSIS
(SINGLE RUNWAY SYSTEM)

NOTE:

The following program is a very generalized description of both the airport system and GPSS programming and should not be interpreted as a working model



Aircraft arrive randomly at TMA boundry

Type a/c assigned randomly from a known distribution

Store airport data (runway length, nbr of gates, etc)

Landing aircraft given priority over departures

If a Class A a/c assign pertinent operational data

If a Class B a/c assign pertinent operational data

If a Class C a/c assign pertinent operational data

If a Class D a/c assign pertinent operational data

Must be a Class E a/c, therefore, assign pertinent operational data

Aircraft enters Terminal Area

Figure 2. Flow Chart for Abbreviated Airport System Simulation Model

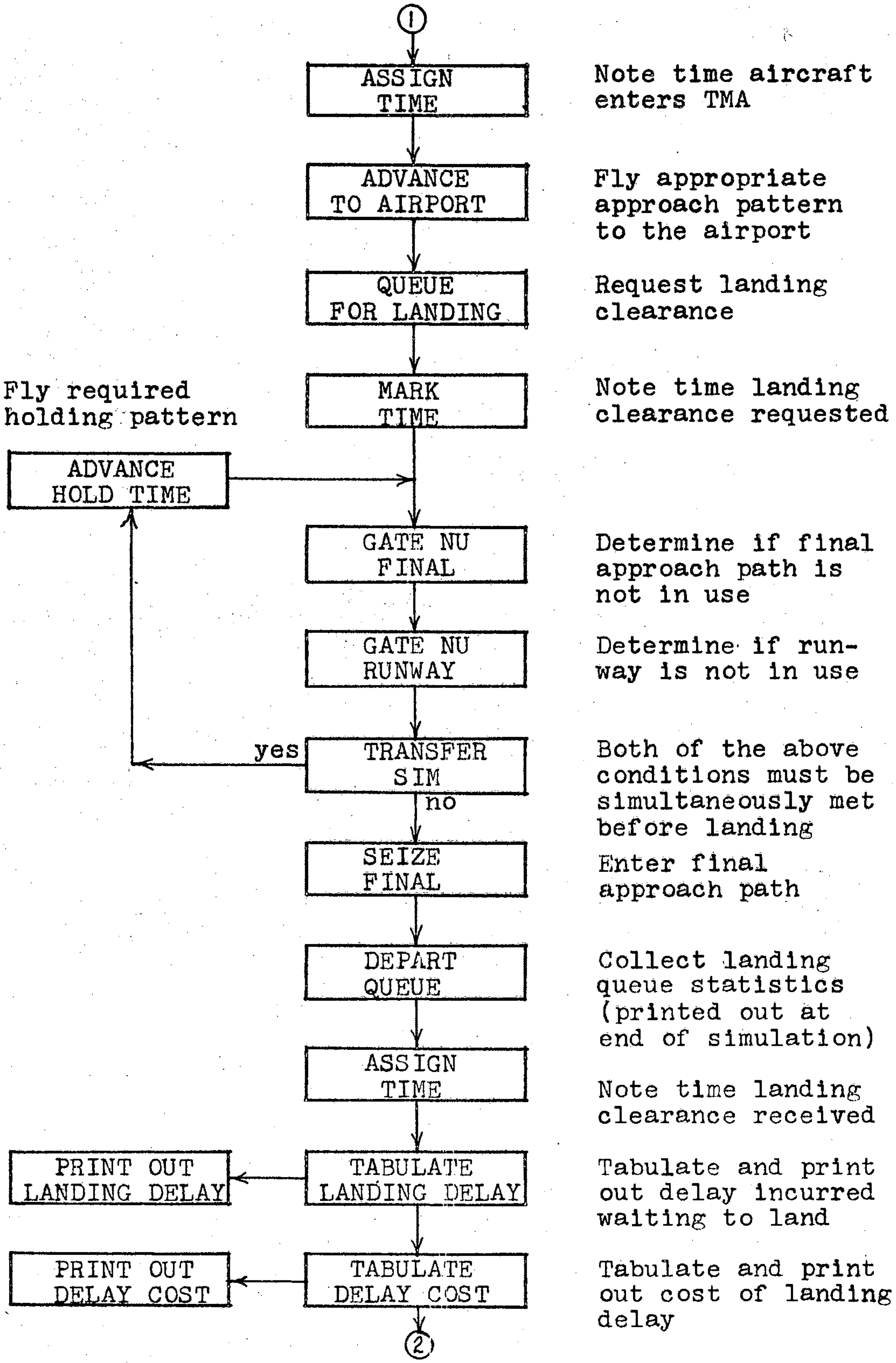


Figure 2. (Continued)

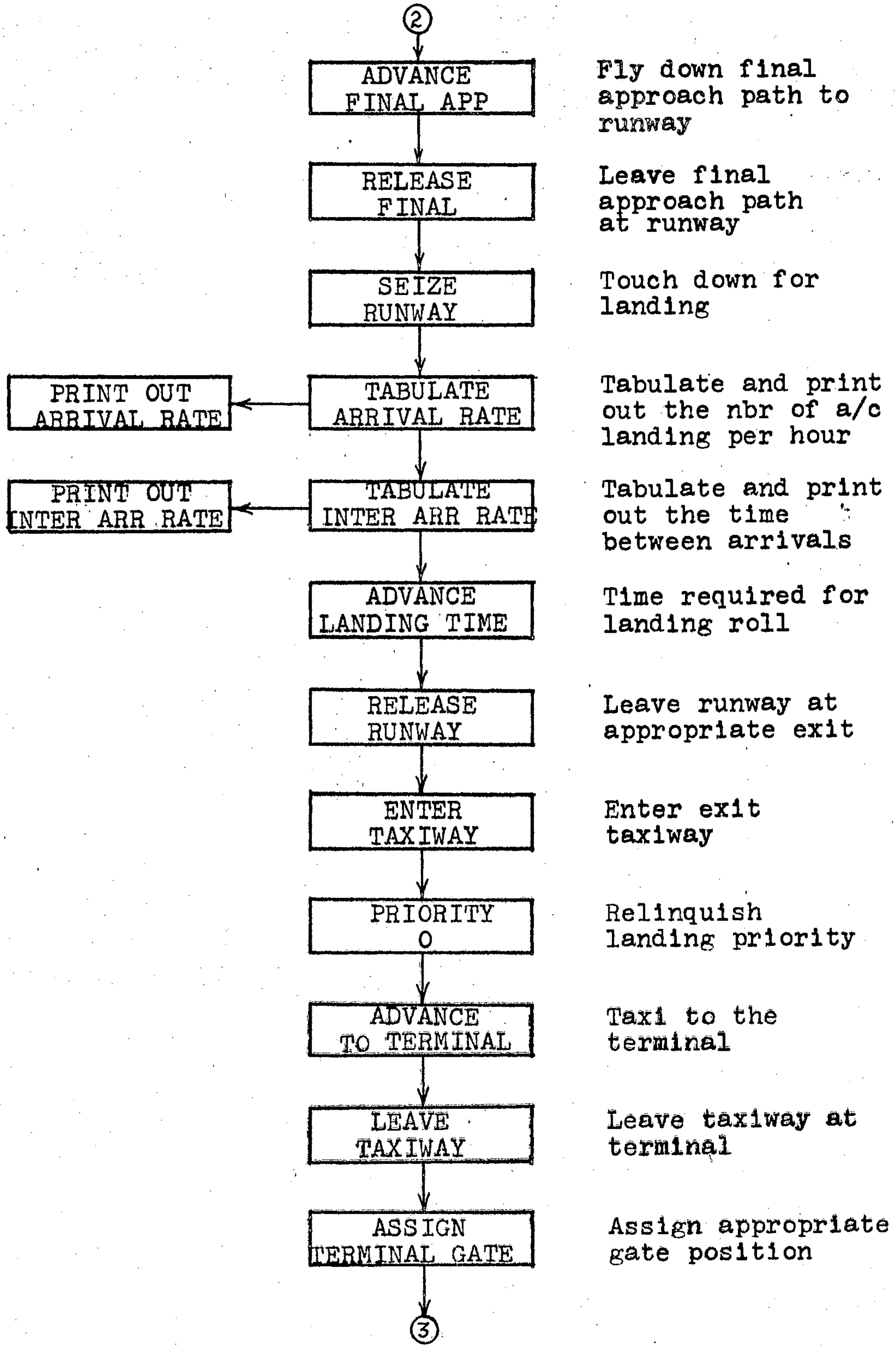


Figure 2. (Continued)

NOTE:

The basic separation requirements, Flight Rule procedures and other pertinent features of the airport system as well as associated GPSS programming techniques are presented in models in Chapter III

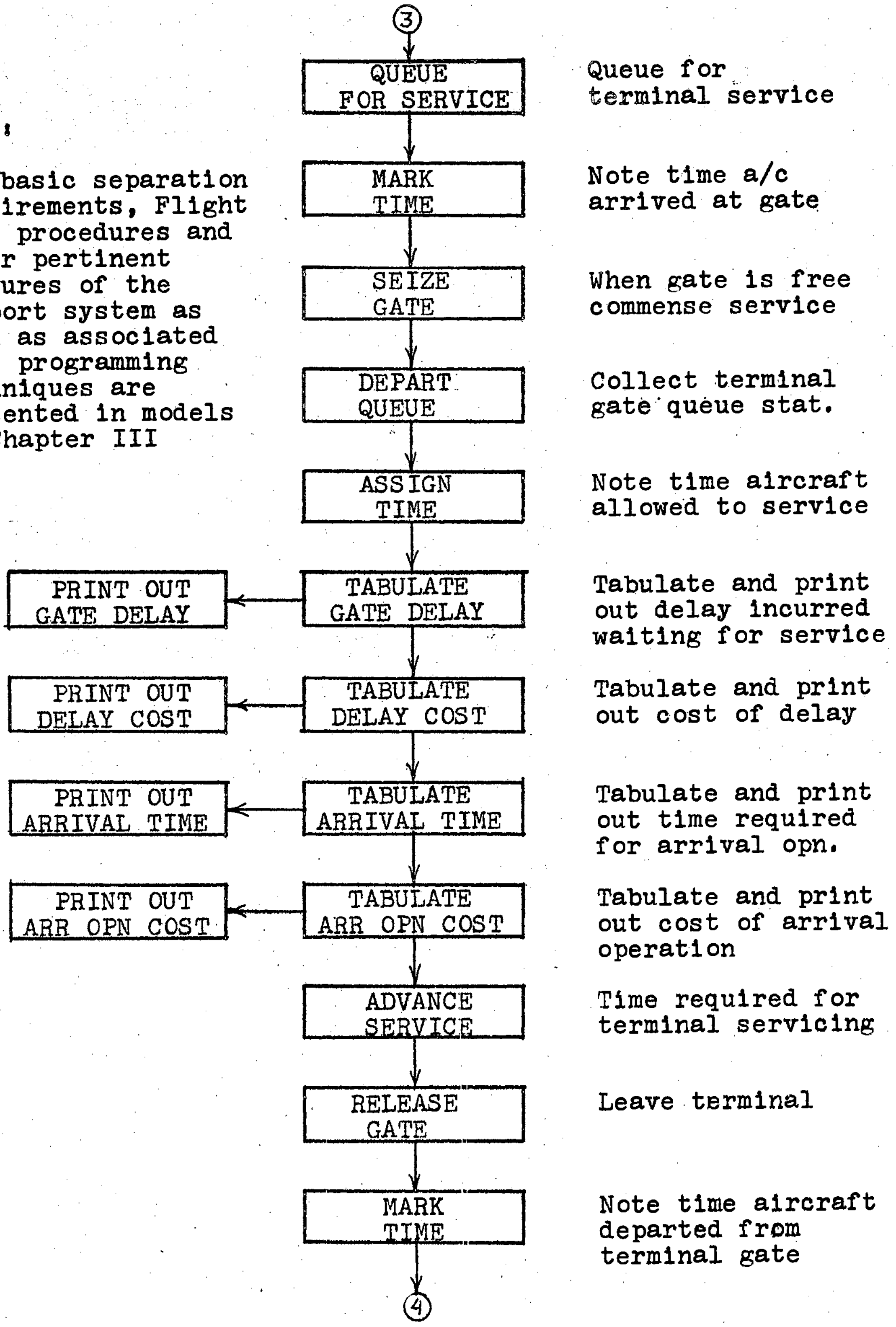
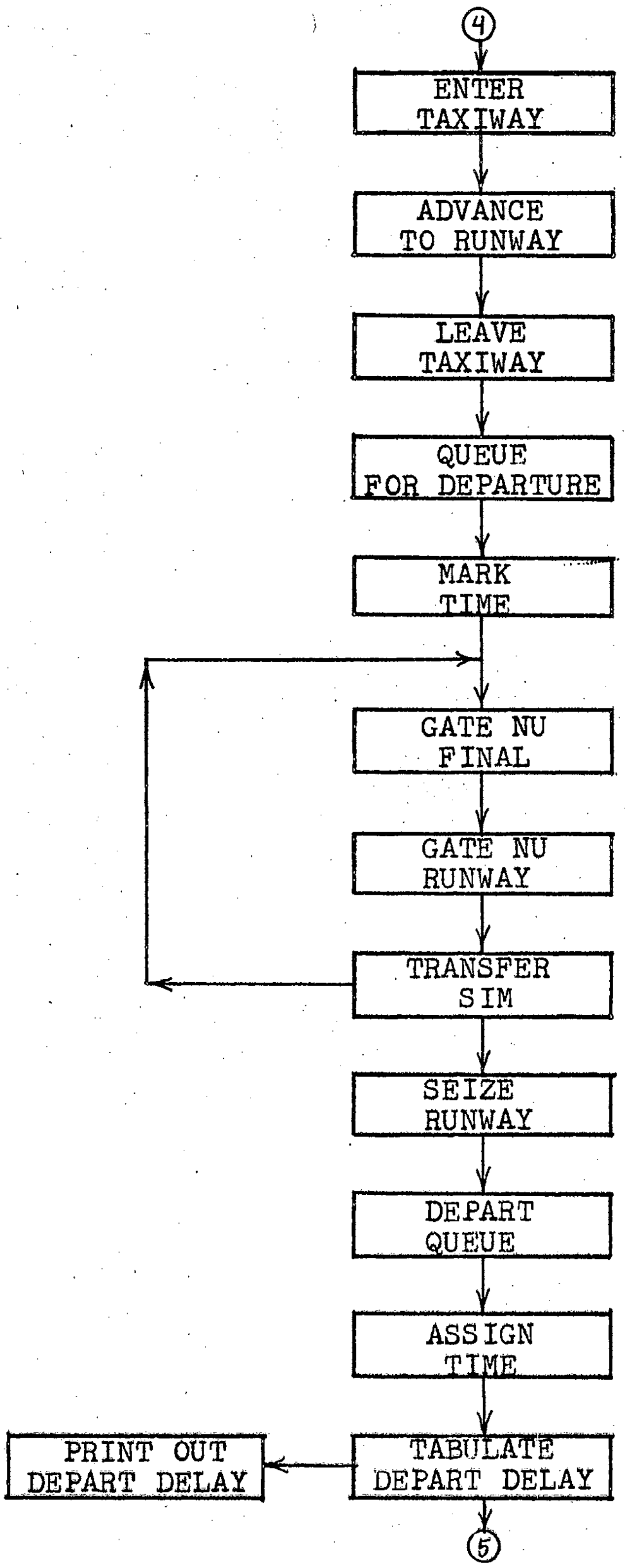


Figure 2. (Continued)



Enter taxiway to runway

Taxi time to runway

Leave taxiway at departure holding point

Request departure clearance

Note time departure clearance requested

Determine if final approach path is not in use

Determine if runway is not in use

Both of the above conditions must be simultaneously met before taking off

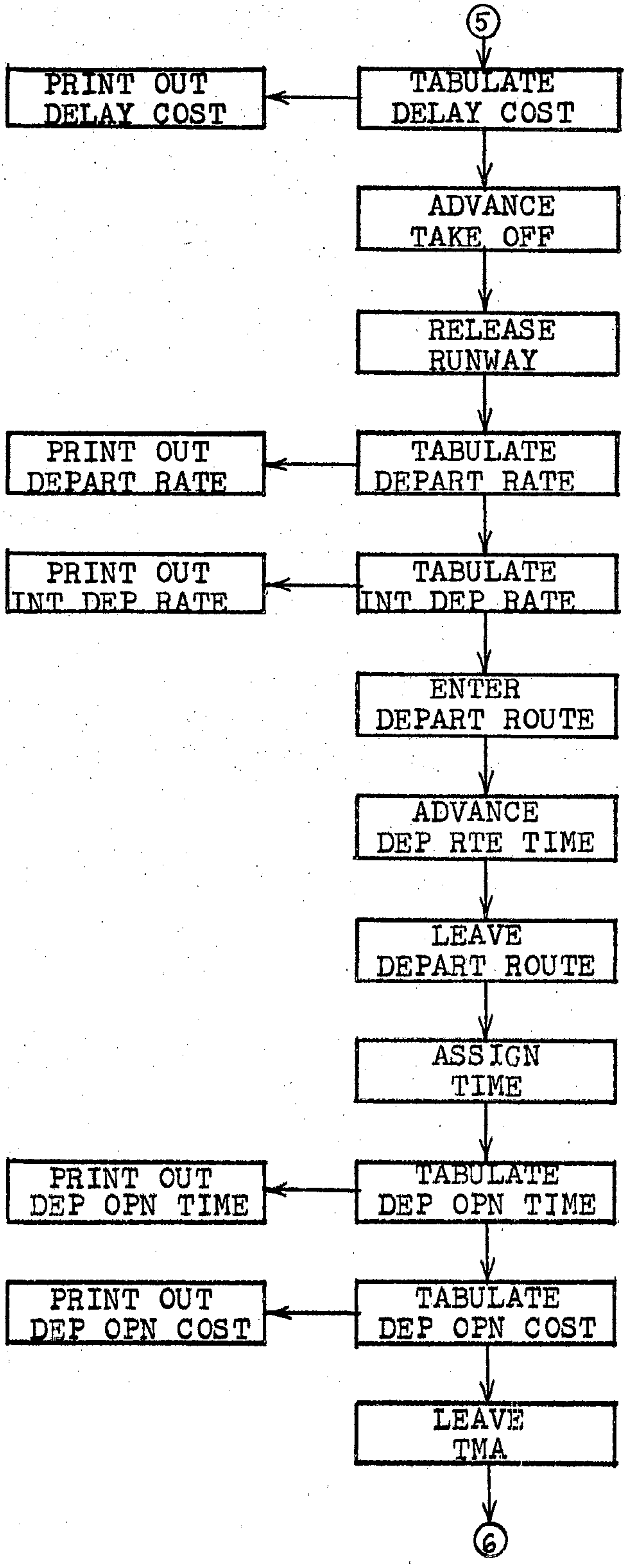
Enter runway for take off

Collect departure queue statistics

Note time departure clearance received

Tabulate and print out delay incurred waiting to take off

Figure 2. (Continued)



Tabulate and print out cost of departure delay

Time required for take off roll

Become airborne

Tabulate and print out nbr of take offs per hour

Tabulate and print out time between departures

Enter departure route

Fly along departure route to TMA boundry

Leave departure route at TMA boundry

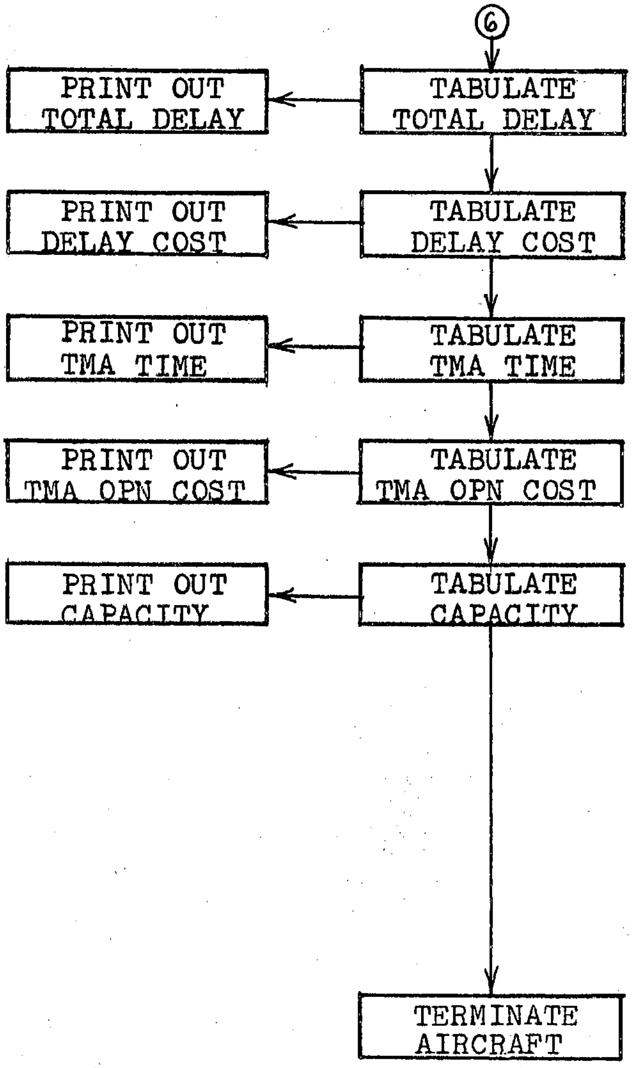
Note time aircraft left departure route

Tabulate and print out time required for departure opn

Tabulate and print out cost of departoperation

Leave TMA and enter airway system

Figure 2. (Continued)



Tabulate and print out total delay incurred in TMA

Tabulate and print out cost of delay

Tabulate and print out total time spent in TMA

Tabulate and print out cost of time spent in TMA

Tabulate and print out total number of landings and take offs per hour

NOTE: An airport's capacity is based on some value of acceptable delay in reaching that level of capacity (i.e., a 2 to 4 min average delay)

Aircraft is removed from simulation model

NOTE 1: A record of facility utilization is automatically maintained by the simulation model and is printed out at the end of the simulation run.

NOTE 2: A discussion on the use of output data from airport simulation models is presented in Chapter IV.

Figure 2. (Continued)

FOOTNOTES

[1] Robert W. Simpson, "Analytical Methods of Research into Terminal Area Air Traffic Operation", Journal of Aircraft, II (1965), p. 185.

[2] Ibid., p. 189.

[3] Terry R. Gonderinger, "An Analysis and Verification of a Computer Simulation System" (unpub. M. S. report, Oklahoma State University, 1968), p. 15.

CHAPTER III

A PROCEDURE FOR COMPREHENSIVE AIRPORT SYSTEMS ANALYSIS

The material in this chapter is advanced on the assumption that the reader has a basic understanding of the subject areas covered in Appendices A and B and has understood the procedural logic of the introductory simulation model presented in Chapter II. In contrast to the introductory model, the following models describe the basic elements of the airport system in the detail required for comprehensive systems analysis. The flow diagrams are constructed as they would be for specific working models. (While the main emphasis of this thesis is on systems analysis rather than computer programming, it is recommended that attention be paid toward the programming techniques that are applied as many of them are not to be found directly in the GPSS manuals.) The following point can not be overemphasized: the models described are not to be interpreted as working models for any specific airport system. They are illustrations of a procedure by which any specific airport system can be modeled. An airport is a very complex system and each airport has many characteristics peculiar to itself. Consequently, it would seem futile to attempt to develop a truly master model which would directly investigate any or all airport systems. However, by relying on the concepts of systems analysis the airport planner may assume that all airport systems have certain basic features in common. Therefore, the goal of this thesis has been to define these basic features of the airport system and to describe them in terms of a simulation modeling logic. Thus it is the logic involved in the airport systems simulation procedure that will be emphasized rather than the specific techniques of programming. It is further assumed that the logic presented in the following simulation procedure is equally applicable to any other simulation technique with only a minimum amount of technical modification required.

In the narrative that follows the number in parenthesis (x) refers to a particular block in the flow diagrams beginning on page 65. The flow diagrams have been constructed in a gravity flow manner which reflects the operation of an aircraft from the time of its arrival at the terminal area boundary through the time it departs the terminal area. The numbering of blocks reflects the path followed by the narrative. Footnotes are used primarily to convey information referring to special programming techniques.

Parametric Versus Statistical Simulation

*In constructing a simulation model the analyst has three basic options as to how he activates or generates transactions (aircraft) within the model; parametrically, statistically, or in combination.

*In parametric simulation pertinent operational data (speed, weight, etc.) of specific aircraft is recorded on a computer tape along with the time the aircraft is due to be activated in the simulation (1, 2). When that time matches the simulation clock time, the aircraft is activated and commences to act in accordance with the dynamics of the airport system being modeled. *An important feature of parametric simulation is that it allows precise control over the characteristics of the aircraft population. Thus actual aircraft, reflecting any amount of individual characteristics, may be simulated. *This is in contrast with the generalized and probablistic character associated with the aircraft population generated in a statistical simulation. Parametric simulation also allows the analyst to hold the aircraft population or airport demand constant while investigating alternatives in system design and operation. A major limitation of parametric simulation, however, is that a great deal of specific aircraft data must be available to the analyst. When planning for future demand, such data is not readily available. Thus it is often necessary to employ statistical methods in defining and activating aircraft in a simulation model. In this method an aircraft is generated (4, 8, ..., 12) and its classification is defined (5, 9, ..., 13) according to appropriate probability functions. The time of generation within a twenty-four hour day is assigned (6, 10, ..., 4) as one of its 100 parameters. The generation time is then tested (7, 11, ..., 5) to insure that the aircraft has been activated in the proper time period.[1]

Terminal Area Entry

Blocks 17 through 19 represent the aircraft identification process. The aircraft is first tested (17) to determine if it is class A.[2] If it is, pertinent operational data is assigned (18) to appropriate parameters and then the aircraft transfers (19) to the Terminal Area (30). If the aircraft is not class A, it is tested (20, 23, 26) until its classification is determined, at which time its operational characteristics are assigned (21, 24, 27, 29) and it is transferred (22, 25, 28) to the Terminal Area (30). Characteristics relating to the physical design of the Terminal Area are provided in savevalues (31). This data includes runway lengths, distance between exits, exit rating, ILS length, etc. A logic switch (32) specifies the weather condition as IFR or VFR.[3] The aircraft tests (33) to determine if the weather condition is IFR. If it is, the aircraft is tested (36) to determine its capability to operate under IFR. If it has no IFR capability it must divert to an airport reporting VFR conditions. The number of diversions is counted in a savevalue (37) and the aircraft is removed from the simulation (38, 39). If the aircraft has an IFR capability it reports to a holding area (40).

If, however, the airport is not experiencing IFR weather (33) the aircraft tests (34) a TMA savevalue (31) to determine whether the airport allows IFR operations in VFR weather. If not, the aircraft commences to fly the appropriate VFR approach pattern (550, page 93). If the airport does allow mixed IFR-VFR operations (as virtually all carrier airports do, since carrier aircraft are usually operated under IFR regardless of weather conditions) an aircraft parameter is tested (35) to determine if the aircraft has filed an IFR flight plan. If it has not, the aircraft commences to fly the appropriate VFR approach pattern to the airport (595, page 96). If, however, an IFR flight plan has been filed, the aircraft reports to the holding area (40).[4] Figure 3 illustrates the basic design of the holding area.

Holding Area Operations

Upon reporting over the holding fix, the aircraft checks the occupancy of the holding stack (41 through 95). Holding level 1 (the lowest) is tested (Gated, in GPSS terms) (41) for its vacancy. If free, the aircraft enters level 1 (91) and requests further instruction from Approach Control. However, if level 1 is occupied, the aircraft checks the next higher levels (42, 43, 45, 46) for the first available space. The number of levels in this stack has been arbitrarily limited to six; consequently, if level 6 is not available the aircraft must be diverted to another holding stack or another airport. The number of diversions

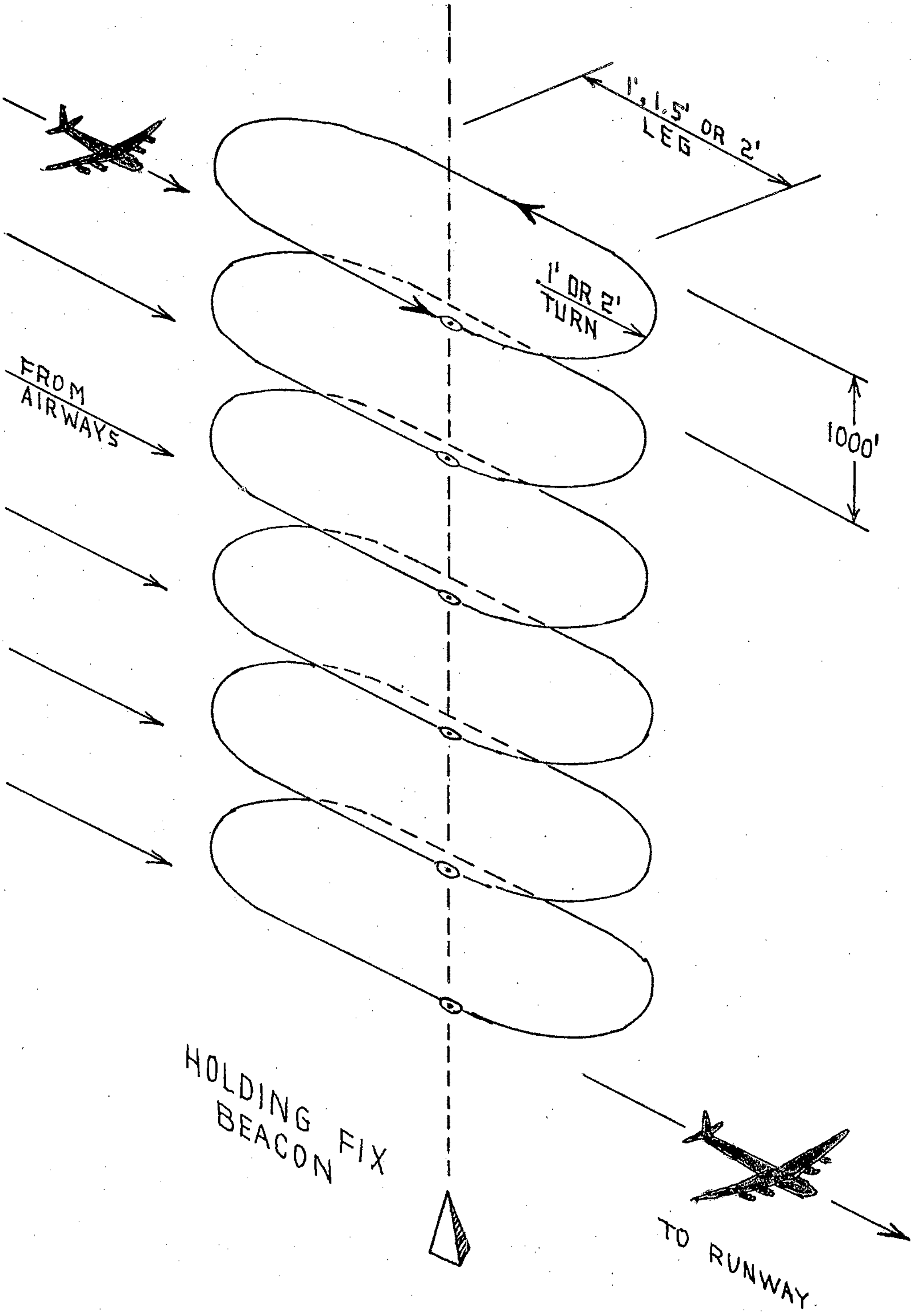


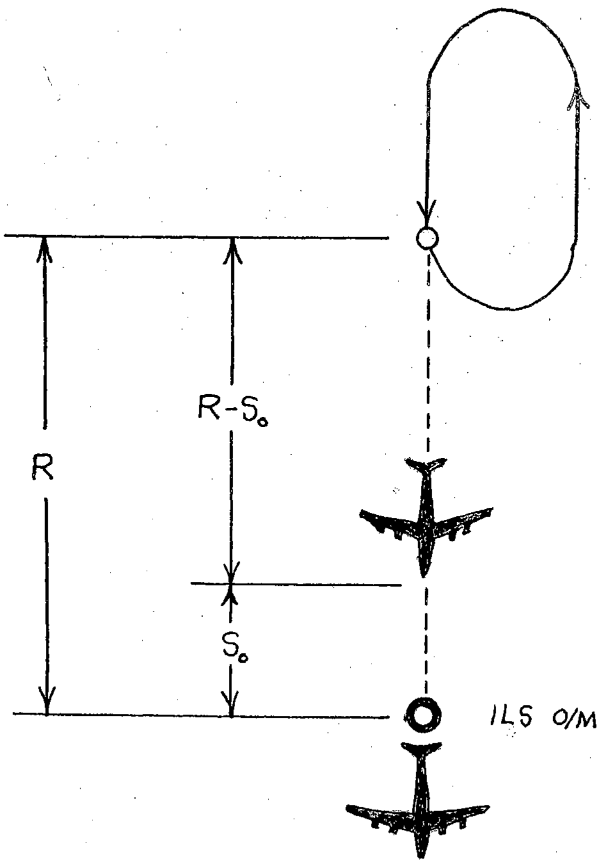
Figure 3. Holding Stack Operation

is counted in a savevalue (47)[5] and since there is only one holding stack in this model the diversions are directed to an alternate airport (48, 49, 50).

If level 6 is vacant the aircraft is assigned to that level (51) and then checks (52) to see if level 5 is vacant. If it is not, the aircraft must fly a prescribed holding pattern (usually a race track pattern consisting of one minute turns and 1, 1.5, or 2 minute straight legs. This pattern of flight is maintained in level 6 until there is notification that level 5 is vacant (the aircraft is not allowed to leave level 6 until the aircraft that was in level 5 has actually reached level 4). The aircraft then notifies Approach Control that it is departing level 6 (55) and descends (or ladders) (56) to level 5. Upon reaching level 5 the aircraft releases (57) level 6 and repeats the above procedure until it reaches level 1 (58 through 90). Upon reaching level 1 Approach Control assigns a priority (92) to the aircraft reflecting its IFR status (applicable only in mixed IFR-VFR traffic).[6]

Regulator Operation

The aircraft next checks (93) the status of the regulator. If the regulator is full[7] the aircraft flies the prescribed holding pattern at level 1 until the regulator has a vacancy (94, 95), at which time it enters the regulator (96). Figure 4 illustrates two of the basic regulator designs. Figure 4a illustrates the regulator for a



(a)

Straight-in Approach

(b)

Procedure turn

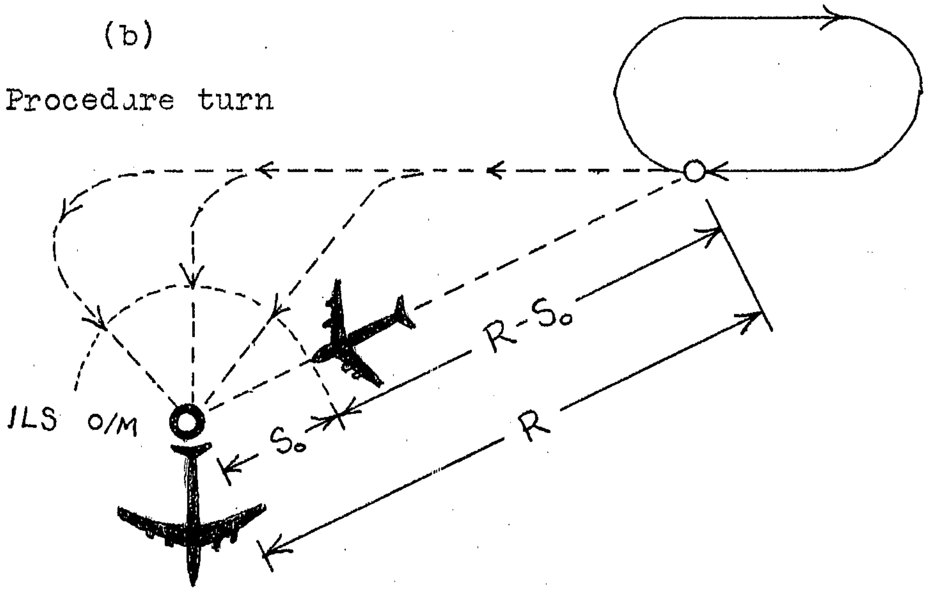


Figure 4. Regulator Operation

straight-in approach while Figure 4b illustrates a regulator incorporating some type of procedure turn. In either case R represents the optimum path from the holding fix to the ILS outer marker while S_o represents the minimum interarrival separation required at the outer marker (currently 3 NM). Any deviation from the optimum path or speed is considered the delay incurred in adjusting to interarrival separation requirements.[8]

The time that the aircraft leaves the holding area (97, 98) is noted (99) and the amount of delay[9] incurred in the holding area is tabulated (100) as is the cost of that delay (101). The aircraft flies the time corresponding to optimum flight from the holding fix to the minimum separation point for the ILS outer marker (102). [Note that aircraft from other holding areas as well as aircraft flying missed approach and touch-and-go re-entry patterns are also being sequenced in the regulator for landing (662/683)]. The aircraft is essentially entering a landing queue (103) that will be used to gather pertinent queuing statistics. The time the aircraft enters the queue is noted (104) and the aircraft commences to accumulate spacing delay (105).[10]

The aircraft first checks to determine if the ILS outer marker separation has been achieved (106) and delays until it has been. Once the ILS outer marker separation has been achieved the aircraft determines whether the required runway separations (t_o = 2 minutes, S_o = 3 NM) can be maintained (107 through 114) and executes delay tactics until the separation minimums have been provided for.[11] Figure 5 illustrates the ILS.

The aircraft is next tested to determine if it is a light aircraft (115, 116); if so, a test determines (117, 118) whether the preceding arrival or departure was a large aircraft causing a wing tip vortice problem.[12] If such is the case, the test determines whether a minimum runway separation can be maintained (usually assumed to be 2 minutes). When these five separation minimums (ILS - S_o, RW - t_o, RW - S_o, AWTV - t_o, DWTV - t_o) are provided for, the aircraft commences to close the 3 NM interval before the ILS outer marker (119). Queue statistics are collected (120), initial landing clearance is noted (121), and regulator delay (the composite delay incurred achieving the required arrival spacing is tabulated (122) along with its associated cost (123). The aircraft flies through the 3 NM interval to the ILS (124) and enters the final approach path (125) at the ILS outer marker.

ILS Operation

After leaving the three mile interval (126) and the regulator (127) the aircraft unlinks (128) the next aircraft in the landing queue for commencement of its landing decision process. Upon entering the final approach path the aircraft enters a programming sequence wherein duplicates of itself are created (129, 130, 141) which are used

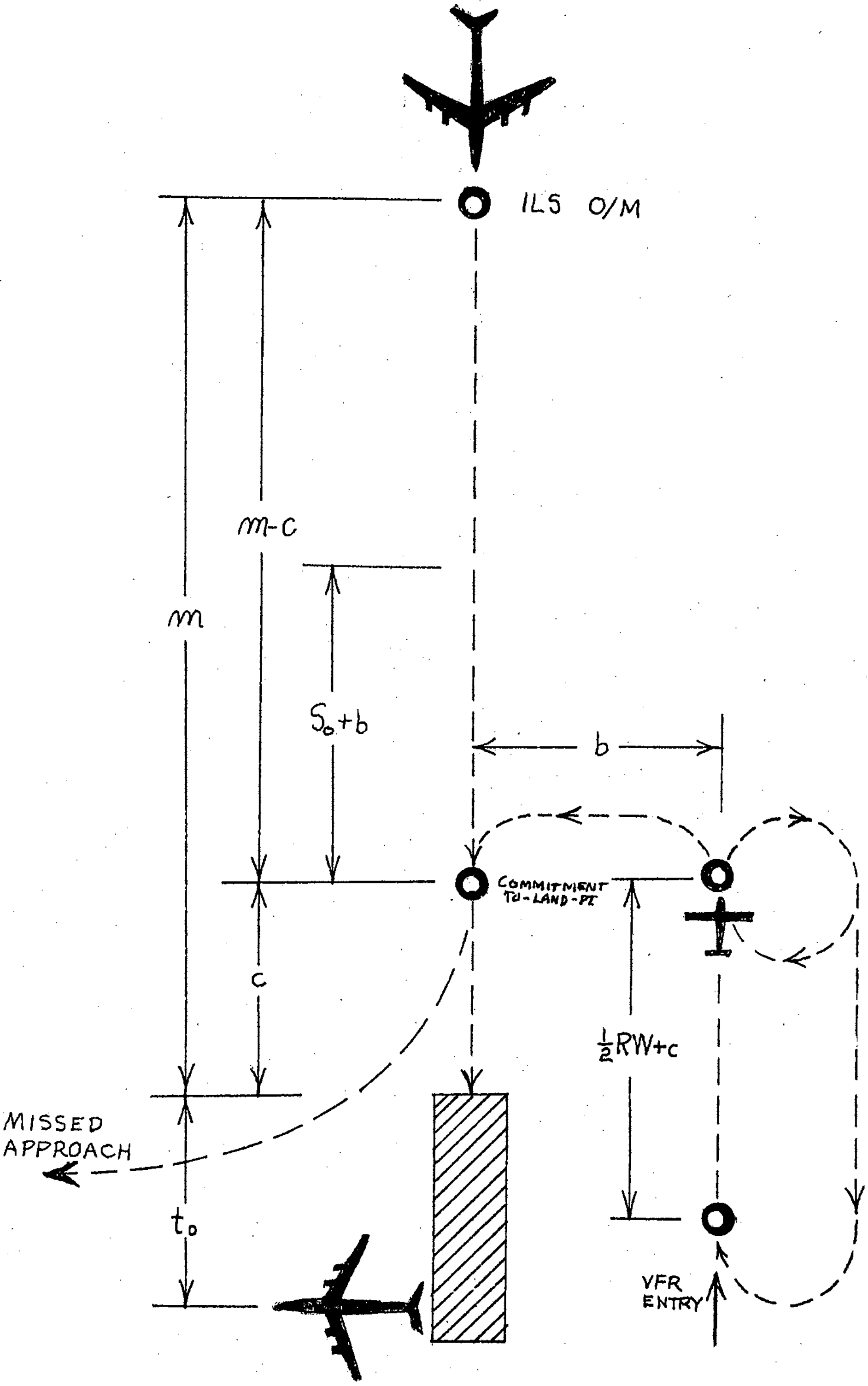


Figure 5. Instrument Landing System (ILS)

to perform pseudo operations independent of the landing operation. Sequence 131 through 135 represents the establishment of the minimum <u>distance</u> separation a departing aircraft must have in front of the aircraft on instrument approach.[13] Sequence 136 through 140 represents the establishment of the minimum <u>time</u> separation a departing aircraft must have in front of the aircraft on instrument approach.[14] Sequence 142 through 146 represents the establishment of the minimum separation a VFR aircraft must have to be authorized to land in front of the aircraft on instrument approach.[15]

The arrival aircraft continues to fly along the ILS to the commitment-to-land point (147). [Note that VFR arrivals are introduced at this point (594, 648)]. The sequence number, the current time, the time required to fly the minimum stabilization distance (also called the commitment-to-land interval) and the required landing time for the aircraft are recorded in savevalues (148-151).[16]

Upon reaching the commitment-to-land point the aircraft (all references to aircraft assume a joint decision effort on the part of the pilot and the controller) checks the occupancy of the commitment-to-land interval (152) and the runway (153). If either is occupied the aircraft must enter a missed approach pattern. However, some of the missed approach aircraft will not want to re-enter the approach pattern (due to low fuel, etc.) thus a statistical transfer (159) is employed to determine the percentage of aircraft likely to continue the missed approach procedure around to the regulator (649-662) and those desiring to leave the terminal area for another airport (164-167).[17]

Commitment-to-Land Operation

If both the CLI and the runway are unoccupied the aircraft is tested (154, 155) concerning its weight classification. If it is a light weight aircraft a check (156, 157) is made to determine if a wing tip vortice problem still exists as a result of a recent landing or take-off by a heavy aircraft. If such a condition does exist it is the pilot's decision whether to land or execute a missed approach. A statistical transfer (158) represents the probability of either choice. A second statistical transfer (160) represents the probability that the pilot decides not to land inspite of having met all landing requirements. Examples of such instances might be a flock of birds in the flight path, pilot error, a gust of wind, or haze.[18] A certain percentage of aircraft that execute a missed approach due to such problems can be expected to request permission to leave the terminal area for an alternate airport (162, 163, 165-167). The others will re-enter the appropriate approach pattern.

The landing aircraft proceeds through the commitment-to-land interval to the runway (168-172) where it is tested for a touch-and-go request (174) which is only authorized during VFR weather (173). The touch-and-go is usually authorized only when the airport is not too busy. Thus a test is made on the status of the regulator (175) and the VFR downwind legs (176, 177) to determine whether a touch-and-go will be authorized.[19]

Runway Operation

As an aircraft lands it increments the arrival rate for the airport (178) as well as the interarrival rate (179). Any holding, regulator or missed approach delay is tabulated (180) as total airborne delay along with its associated cost (181). Next the total time spent airborne after entering the terminal area is tabulated (182) along with the total operational cost for that time (183).

The landing aircraft is tested to determine if it has a heavy classification (184, 185). If it does, a duplicate transaction is created (186) to perform a pseudo operation for establishing a time separation criteria for subsequent light aircraft operations (187-189).

The runway is broken up into segments representing distances between intersections or exits. (Figure 6 illustrates the airport layout.) The aircraft proceeds along the first segment at its appropriate landing speed (192, 193). At Exit 2 the aircraft is tested (194) to determine if it is a class E aircraft. If it is, a statistical transfer (195) is employed to specify the probability that the aircraft leaves the runway at Exit 2 (306). If the aircraft is not class E, it is next determined whether it is class D (196).

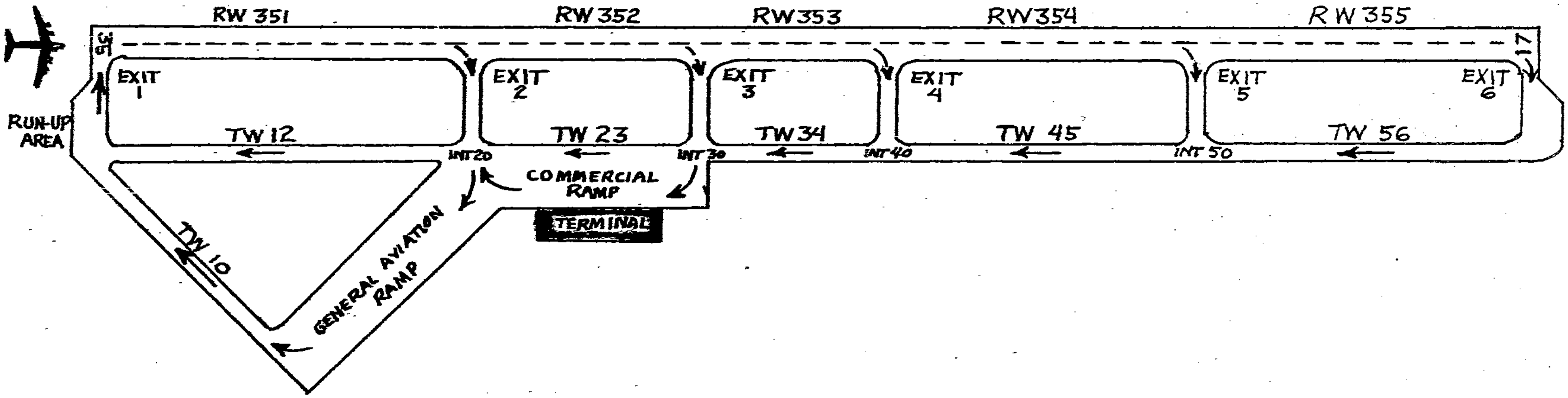


Figure 6. Airport Layout

If it is, a statistical transfer (197) sends a certain percentage of class D aircraft into Exit 2 (306). If the aircraft has not left by Exit 2 it continues on into the next runway segment where similar tests are performed until the aircraft has exited the runway (198-224).[20]

Taxiway Operation

For the purpose of this narrative it will be assumed that the aircraft currently under consideration is a class B aircraft and that it has left the runway at Exit 5 (237). Upon leaving the runway (238, 239) the aircraft loses its landing priority (which was a value of three or greater) and receives a priority equal to zero (240). The time the aircraft entered the taxiway system (241) is noted for use in later computing the total time spent in the taxiway system. The aircraft taxis along the exit taxiway (242) to the taxiway intersection. As any aircraft already on the taxiway has a priority equal to one, the aircraft leaving (243) an exit taxiway notes its time of arrival at the intersection (244) and joins a queue (245) for admittance to the intersection. Once the intersection is free the aircraft moves into it (247) [at which time queue statistics are gathered (248),[21] the intersection delay is noted (249) and the delay (250) and its associated cost (251) are tabulated]. The high-speed exit priority is assigned (252) (effects only aircraft entering from an exit) and the aircraft taxis through the intersection (253) and on through the next taxiway segment (254-259). This procedure is repeated along the taxiway until the aircraft approaches the ramp area. Upon entering Intersection 30 (292) queue statistics are gathered (293), intersection delay is noted (294), tabulated (295) and cost accounted (296). The aircraft receives taxiway priority (297) and taxis through the intersection. A test is made to determine if the aircraft is a general aviation type (298, 299). If not, the aircraft enters the commercial ramp (440). If the aircraft is a general aviation type it proceeds through the next taxiway segment (300-303) and queues for Intersection 20 (305). (There are three queues of traffic competing for this intersection. The traffic entering from Exit 2 has a zero priority; the traffic entering from the commercial ramp has a priority of two; while traffic on the taxiway has a priority of one.) After entering the intersection (316), collecting queue statistics (317), noting intersection delay (318), tabulating the delay and its costs (319, 320), receiving the taxiway priority (321) and moving through the intersection (322), a test is made (323, 324) to direct general aviation aircraft to their ramp area (483). The commercial aircraft taxi to the departure holding area where they join aircraft arriving from the general aviation ramp (547-549).

Holding Ramp Operation

At the departure exit a test (329) is made for jet aircraft. If the aircraft is not a jet it enters the run-up apron (330) for required run-up operation (331) before re-entering the departure exit (332-334). Jet aircraft do not usually require a lengthy run-up as do reciprocating engine aircraft and thus are able to move directly to the departure queue.[22] Upon entering the exit (334)[23] total taxiway delay (336), delay cost (337), operating time(338) and operating cost (339) are tabulated. The aircraft joins the departure queue (340), notes the time it entered the queue (341), and links onto a user chain (342). The aircraft currently first in line for departure places its expected time required for take-off in a savevalue (343).[24]

Departure Operation

A test (344) is next made to determine if the airport is currently experiencing IFR weather conditions. If not, a test (345) is made to determine if the airport is allowing mixed IFR-VFR traffic. If so, a test (346) is made to determine if the aircraft has filed an IFR flight plan. All VFR departures check to see if the minimum separation with respect to arrival aircraft is maintained (347); if there is a wing tip vortice problem resulting from a recent arrival or departure aircraft (348, 350); and if the runway is unoccupied (349). When these four conditions are simultaneously met (351), the aircraft is authorized to enter the runway for take-off (360). All IFR departures record the current time in a savevalue (352) which will be used in subsequent departure time computations. A departure aircraft checks to see if the runway is unoccupied (353); if the required separation between departures can be maintained (354); if the required separation before an arrival aircraft is maintained (355); and, if a light aircraft (356 357), whether wing tip vortice departure delay has been met (358, 359). If any one of these conditions is not met, the savevalue time (352) is upgraded and the test sequence is repeated until all conditions are met. The aircraft is then allowed to enter the runway for take-off.[26]

Departure queue statistics are gathered (361) and a statistical transfer determines the possibility that the aircraft aborts its take-off (362). An aborted take-off taxis down the runway to Exit 2 (363, 364) where a test is made (365, 366) which directs general aviation aircraft into Exit 2 (375). Upon leaving the runway (376, 377) the aircraft unlinks (378) the next aircraft in the departure queue for commencement of its departure decision process.

Commercial aircraft proceed to Exit 3 where they leave the runway and unlink the next aircraft for the departure decision process (367-374).

Aircraft ready and authorized to take off note their departure delay (380); tabulate that delay (381) and its cost (382); and move onto the runway for take-off (clear-to-take-off time or CTO) (383).

A test is made to determine if the aircraft preparing to take off is a heavy aircraft (384, 385) and, if so, a duplicate transaction is created which performs a pseudo operation for establishing a time separation for subsequent light aircraft operations (387-391).

Departure Route Operation

The aircraft takes off (392) and enters the departure route (393). Upon leaving the runway (394) the aircraft unlinks (395) the next aircraft in the departure queue for commencement of the departure decision process. The departure rate (396) and interdeparture rate (397) are tabulated at the time the aircraft clears the runway.

A test is made for IFR weather conditions (398). If VFR, the aircraft is able to establish lateral separation upon clearing the runway and there is, in effect, no common departure path (399). The VFR departure flies to the terminal area boundary (400).

If the departure is operating under IFR it flies the length of the common departure route $[d]$ plus the interdeparture separation requirement $[S_o]$ and notes the time it reaches that distance from the runway in a savevalue (403). The aircraft then flies the remaining distance to the terminal area boundary (404, 405). Figure 7 illustrates the departure route.

Airport System Performance Data

Upon leaving the terminal area (406) the total time required for the departure operation (407), its associated

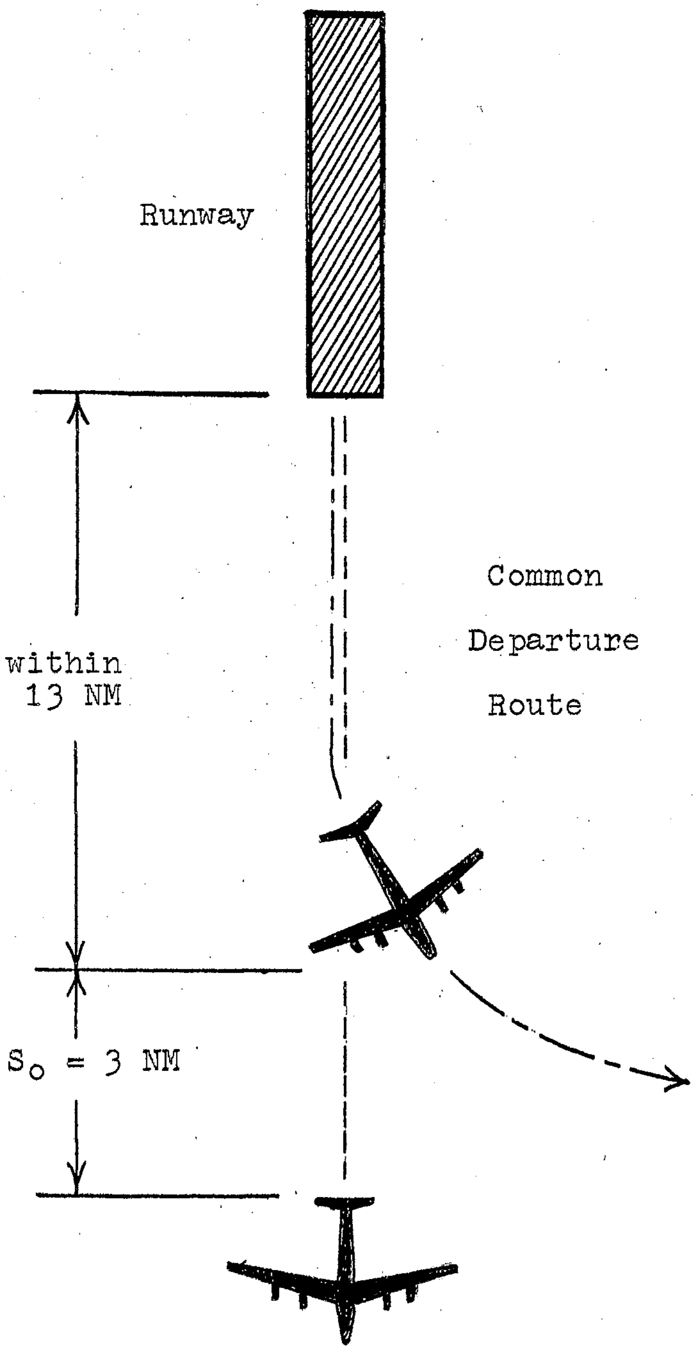


Figure 7. Departure Route Operation

cost (408), and the airport capacity (total number of operations per hour) (411) are tabulated.

If the aircraft is class A (412) its total delay (413), the cost of delay (414), the total terminal area time (415), and the associated cost (416) are tabulated. This break-out of data is also provided for the other aircraft classes (417-435).

If it is desirable, tabulated data may be printed (438) out at the end of each hour of simulation by testing the current clock time with respect to increments in multiples of 3600 seconds (436, 437). At this point the activities of the transaction (aircraft) are terminated in the simulation (439).

Commercial Ramp Operation

Sequence 441-482 represents the commercial ramp model. Upon leaving the taxiway intersection (441) a ramp operation priority of zero is assigned (442). Next a tabulation is made for total delay incurred while taxiing (443), the cost of that delay (444), the total time spent taxiing (445), and the total cost for the taxiway operation (446). The aircraft taxis through the ramp to the terminal (447) where it joins a queue for terminal service (448). The time the aircraft joins the queue for terminal service is noted (449) and it then links onto a user chain (450).[27]

A Transfer-All condition is tested (451) whereby the aircraft is assigned to the first gate position that becomes available.[28] Upon entering the first available gate position (452, 455, 457 or 460) the aircraft records the gate position number in a parameter (453, 456, 458 or 461) which then allows a programming simplification called indirect specification to be used. Since the operation of each gate is essentially the same, the four gate service processes can be resolved into one (454, 459, 462) in which the argument for a particular gate is not directly specified; rather an address (gate number in an aircraft parameter) where the argument can be located is specified. The aircraft departs the queue specified by the gate number carried in one of its parameters (463). Queue statistics (463) and terminal delay (464) are recorded while tabulations are made for terminal delay (465), delay cost (466), arrival rate 467), interarrival rate (468), total arrival delay incurred during approach, taxiway and terminal ramp operation (469), the associated cost (470), the total time spent reaching the service point from the terminal area boundary (471) and the total cost of the arrival operation (472).

The next aircraft in the queue is unlinked to seek terminal service (473), the aircraft receives its service (474) and then leaves the gate position (475). The time of departure is noted (476) and the aircraft taxis through the terminal ramp to the taxiway (477). The time the taxiway intersection is reached is noted (479), a priority of two is assigned (480) and the aircraft joins a queue for the taxiway intersection (481-482).

General Aviation Ramp Operation

Sequence 484 through 546 represents the general aviation ramp model. Upon leaving the taxiway intersection (484), a ramp priority of zero is assigned (485). Tabulations are made for total delay incurred in the taxiway system (486), the delay cost (487), the total time spent in the taxiway system (488), and the total cost of the taxiway operation (489). After taxiing through the ramp to the parking area (490) tabulations are made for the arrival rate (491), interarrival rate (492), total arrival delay (the sum of any holding, regulator, missed approach or taxiway (delay) (493), the arrival delay cost (494), the total time required for the arrival operation (495), and the arrival operation cost (496).

A test is made to determine if the aircraft is a locally based craft (497). If so, it enters the local parking and hangar area (501). If the aircraft if not of local registration, it enters the transient area (498) where a count is made of the number of transient stops (499). A statistical transfer is used to designate the percentage of transient aircraft "remaing-over-night" or RON (500). The RON aircraft park in the local area (501). A count of the number of aircraft entering the local area is made (502) and then the aircraft registration is tested (503). If the aircraft is locally registered, tabulations are made for total arrival delay (504), delay cost (505), total arrival time (506) and cost of arrival operation (507). A similar tabulation is made for the RON aircraft (508-512). The activities of these aircraft are then temporarily terminated (513).[29]

The non-RON transient aircraft are counted (514) and the time of their arrival is noted (515) as they queue for service (516). Upon receiving service (517) queue statistics are gathered (518) and the time service is begun is noted (519). Tabulations are made for the service delay (520) and delay cost (521). After receiving service (522) the aircraft leaves the service point (523), taxis to the taxiway for departure (542-546).

A generation sequence similar to that described at the beginning of this chapter is represented by blocks 524 through 539. The time periods are arbitrarily selected (i.e., 6 a.m.-10 a.m., 10 a.m.-2 p.m., 2 p.m.-6 p.m. represent the likely periods of general aviation aircraft activity). As mentioned earlier, parametric simulation or a combination of statistical and parametric simulation techniques may also be employed.

Upon leaving the local area (540, 541) the aircraft marks its departure time in a parameter (542) and taxis to the taxiway (543-546).

VFR Trombone Operation

Sequence 550 through 594 represents the VFR "trombone" approach model. Figure 8 illustrates the basic features of the approach pattern.[30] The most significant features involve the criteria for turning onto base leg. These criteria are as follows: (A) If no aircraft is landing in front of the aircraft under consideration that aircraft need only fly downwind beyond the runway a distance equivalent to the minimum stabilization distance [c] before turning from the dowwind leg onto the base leg. This results from the assumption that all VFR approaches use a squared pattern consisting of at least downwind, base and final legs. (See Figure 8a). (B) If the preceding landing aircraft is turning on final and is closer to the runway than the aircraft under consideration, the latter aircraft may turn onto base. (See Figure 8b). (C) If the preceding landing aircraft has turned onto final but is further from the airport than the aircraft on downwind, the latter aircraft must continue downwind until the preceding aircraft passes by on final. (See Figure 8c).

Due to the complexity of the logic in this particular model, material that has previously been allocated to footnotes will be carried in the main text.

Random VFR arrivals fly from the terminal area boundary (550) to the downwind leg entry point (which is assumed to correspond to the runway mid-point) (551). Missed approach and touch-and-go re-entries are also made at this point (660, 682).

Upon entering the downwind leg the aircraft is tested

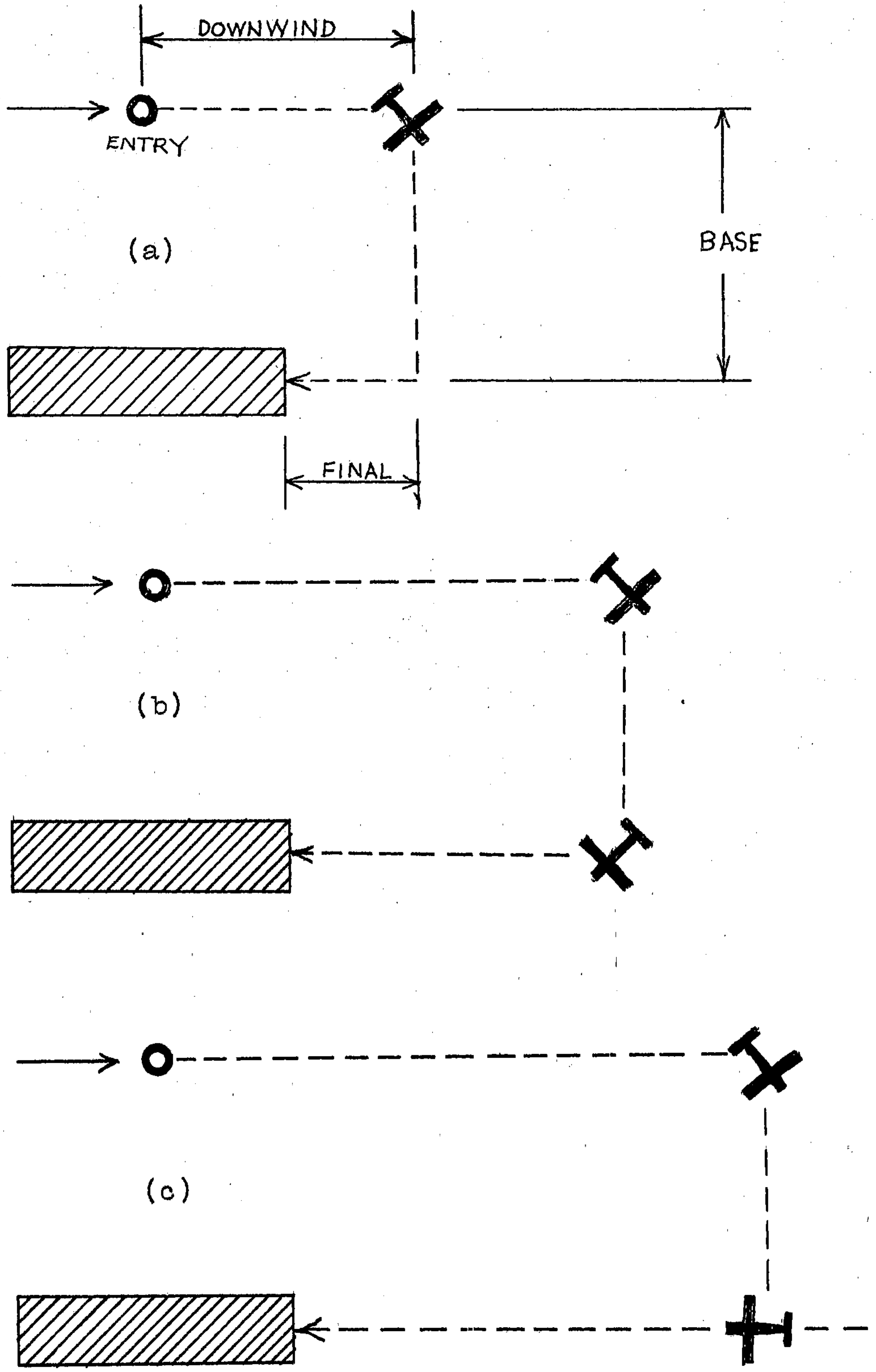


Figure 8. VFR Trombone Operation

to determine if it is jet or reciprocating engine (552). Jet aircraft are assigned to the 1500' flight level (553) while reciprocating engine aircraft are assigned to the 1000' flight level (557).

Assuming that the optimum (or earliest) point where an aircraft on downwind could turn onto base is at a distance ($\frac{1}{2}$ RW + c) from the entry point, the arriving aircraft flies that distance (554, 558). Upon reaching the point for optimum turn onto base (i.e., $\frac{1}{2}$ RW + c) a landing sequence number (N) is assigned (560) and the arrival time at that point is noted (561) and further designated (C0). In addition, the current time is recorded (562) and designated (C2). [Initially C0 and C2 are equal in value; however, the value of C0 (561) is static while the value of C2 (562) is continuously incremented as long as the aircraft continues on the downwind leg.]

Next, a test is made to determine if the aircraft that has most recently turned on final is the N-1 aircraft in the landing sequence (563). C2 (562) is incremented by a unit of time every time this condition is not met and the test is repeated. When the aircraft most recently to have turned on final [designated (x)b] is the N-1 aircraft, a test is made to determine whether the N-1 aircraft has passed by on final (564). Specifically, if the current time, C2, is equal to or greater than the time the N-1 aircraft is due to arrive at the commitment-to-land point (i.e., C1 + fMP, where C1 is the time the N-1 aircraft turned on final and fMP is the time it takes to fly down final to the commitment-to-land point) then the N-1 aircraft has passed by on final and the N aircraft may turn on base (567). If, however, the N-1 aircraft has not passed by on final, the N aircraft must continue downwind until the N-1 aircraft has passed by on final. Specifically, the distance covered by the N aircraft between time C0 and the current time C3 (i.e., C3 - C0) must be equal to or greater than the distance remaining to be covered by the N-1 aircraft on its path to the commitment-to-land point (i.e., C1 + fMP - C3). This condition is tested for each unit of simulation clock time and whenever the condition is not met the current time C3 (565) is incremented and the test is repeated.

After turning onto the base leg (567) from the downwind leg (568), the time spent in the downwind leg after reaching the optimum turning point (i.e., $\frac{1}{2}$ RW + c) is recorded as MP in a parameter (569). Noting that the tail wind condition that an aircraft experiences while on downwind will cause it to cover more distance on the downwind leg in a given period of time than it will cover for a similar period on final, a wind factor (f) is introduced. The value fMP is then recorded in a parameter as the time required for the aircraft to fly its final approach leg (570). (This wind factor results in the creation of excessive interarrival gaps if the trombone becomes greatly extended under strong wind conditions.)

A duplicate transaction is created to perform a pseudo operation for establishing separation criteria for a departure desiring to take off in front of an arrival (571). The basic assumption made is that a take-off can be authorized in front of a VFR arrival on base or final provided it can clear the runway before the arrival is ready to land. The time the landing aircraft turns on base is noted (572) and a test is made to determine whether the take-off time of the aircraft currently awaiting departure is less than or equal to the time required for the arrival to fly its base and final legs. If so, the approach time of the landing aircraft establishes the departure separation criteria (575). Otherwise the take-off time, RW(x), of the aircraft currently awaiting departure establishes the departure separation criteria (577). In this latter case the landing aircraft covers a time period equivalent to the base leg entry time minus the departure separation time [i.e., Cl - RW(x)] before activating the facility representing a departure clearance refusal (580-583). (The departure aircraft tests the status of this facility during its departure clearance process.)

The length of the base leg should reflect the required interarrival separation for the runway, thus the length of the base leg for the N aircraft is assumed to be the landing time RW (N-1) of the preceding arrival (584). The landing sequence number of the aircraft is recorded, (x)b, as it turns onto final (585) along with the current time, Cl (586); the time required to fly the final approach leg fMP (587); and its expected landing time RW (588). The aircraft proceeds down final to the commitment-to-land point (589-591) where it records its airborne or landing delay (592) and the associated delay cost (593).

It should be noted that the above is a formalized description of the VFR trombone operation in the sense that there is little or no ground control involved. Consequently, traffic control is undertaken by the individual pilots. This results in a wide range of performance characteristics that are basically informal and thus very difficult to analyze or simulate.

VFR Approach Operation in Mixed IFR-VFR Traffic

Sequence 595 through 648 represents the VFR approach model for mixed IFR-VFR traffic conditions. (See comments at the end of footnote 30; see also Figure 5, p.40)

As with the previous VFR approach models, aircraft arrive essentially on a random basis at the entry point to the downwind leg. Vertical separation is established between jet and reciprocating engine aircraft (596) and the aircraft fly downwind (597-603) to a holding point just off the end of the runway. The aircraft queue for landing clearance (604), note the arrival time (605), and link onto a user chain (606). (Note that jet aircraft have priority in the landing sequence over reciprocating engine aircraft due to their higher fuel consumption rates.)

After reaching the initial landing decision (or clearance) point (607), queue statistics are collected (608), the time required to fly the base leg is pre-determined (609) and the current time is recorded (610).

A test is made to determine if the most recent aircraft to reach the commitment-to-land point can land and clear the runway (Cl + RW) before the aircraft currently under consideration can reach the commitment-to-land point (611). If this condition is met, a check is made to see if the required separation (3 NM) can be maintained in front of an instrument approach (612). If so, a test is made for light aircraft (613, 614) which must test the status of the wing tip vortice problem on the runway (615, 616). A statistical transfer determines the percentage of aircraft which will decide to land inspite of a vortice problem (617). If the aircraft is unable to land it tests the status of the landing queue (618) and if there are no aircraft close behind it the aircraft executes a 360 degree turn (619), increments its clock time (610), and repeats the decision process (611-617). If the aircraft cannot execute a holding turn because of traffic behind it (618), it executes a "go around" procedure which takes it back to the downwind leg entry point (620-627). Holding delay (625) and delay cost (626) are tabulated for subsequent print out.

Aircraft meeting the landing requirements turn onto base leg (628), unlink the next arrival aircraft for the landing decision process (630) and record the airborne (or landing delay (631).

As in the preceding VFR approach model, a duplicate transaction is created to perform a pseudo operation for establishing the separation criteria for a departure desiring to take off in front of an arrival (632). The assumption underlying the criteria is that the departure must be able to clear the runway before the arrival is ready to land. A test is made to determine if the time required for the arrival to fly its base and final legs (b + c) is less than or equal to the time (RW) required for the departure to take off (634). If so, the value (b + c) is used as the separation criteria (635), otherwise the vale (RW) is used (636). In the latter case the arrival aircraft flies for a period of time (b+c - RW) (637) before activating the "no departure" facility (639-642). (A departure aircraft must, check the status of this facility and if it is in use, take-off clearance is refused.)

Missed Approach Operation

Sequence 650 through 662 represents the missed approach re-entry procedure model. It is assumed that the missed approach procedure allows the aircraft to break away from the runway as quickly as possible. Upon leaving the final approach (650) the number of missed approaches is counted (651) and the aircraft flies the prescribed missed approach procedure (652). Any time spent performing a missed approach procedure is considered delay; consequently, the amount of delay and its associated cost are determined and tabulated

(653-656). The aircraft next tests for IFR weater conditions (657). If the weather is VFR, a test is made to determine if the airport is allowing mixed IFR-VFR operations (658). If so, a test is made for aircraft filing IFR flight plans (659). Blocks 660-662 direct aircraft to the appropriate re-entry area.

Touch-and-Go Operation

Sequence 664 through 682 represents the touch-and-go re-entry procedure model. The number of touch-and-go operations is counted (664) and the aircraft executes its touch-and-go procedure on the runway (665). A statistical transfer (666) determines the percentage of aircraft that elect not to re-enter the approach pattern. These aircraft depart the terminal area for another airport (667-670).

Aircraft that request permission to re-enter the approach pattern test a statistical transfer used to designate the probabilty that an aircraft will request a full stop landing (671). Such aircraft are authorized to re-enter the approach pattern via a "go-around" procedure (676-684). If an aircraft desires only to attempt another touch-and-go, the status of the approach system must be checked (672-674). If the airport is considered too busy, the aircraft is not allowed another touch-and-go and a statistical transfer (675) is used to determine the percentage of aircraft that will then request a full-stop landing. (The definition of an airport too busy to allow touch-and-go operations is strictly the controller's interpretation; however, this model assumes that the occupancy status of the regulator and the downwind legs determine the activity level of the airport with respect to authorizing a touch-and-go operation.) Aircraft not authorized another touch-and-go depart the terminal area for another airport (667-670).

In closing this chapter, the point is re-emphsized that these models have been developed as illustrations of a procedure rather than as descriptions or working models of any specific airport system or problem. There are innumerable variations among airports in both design and operation; however, it is hoped that the procedure just described provides sufficient insight into the use of computer simulation and airport systems analysis to provide the interested analyst or planner with the capability for developing his own simulation models.

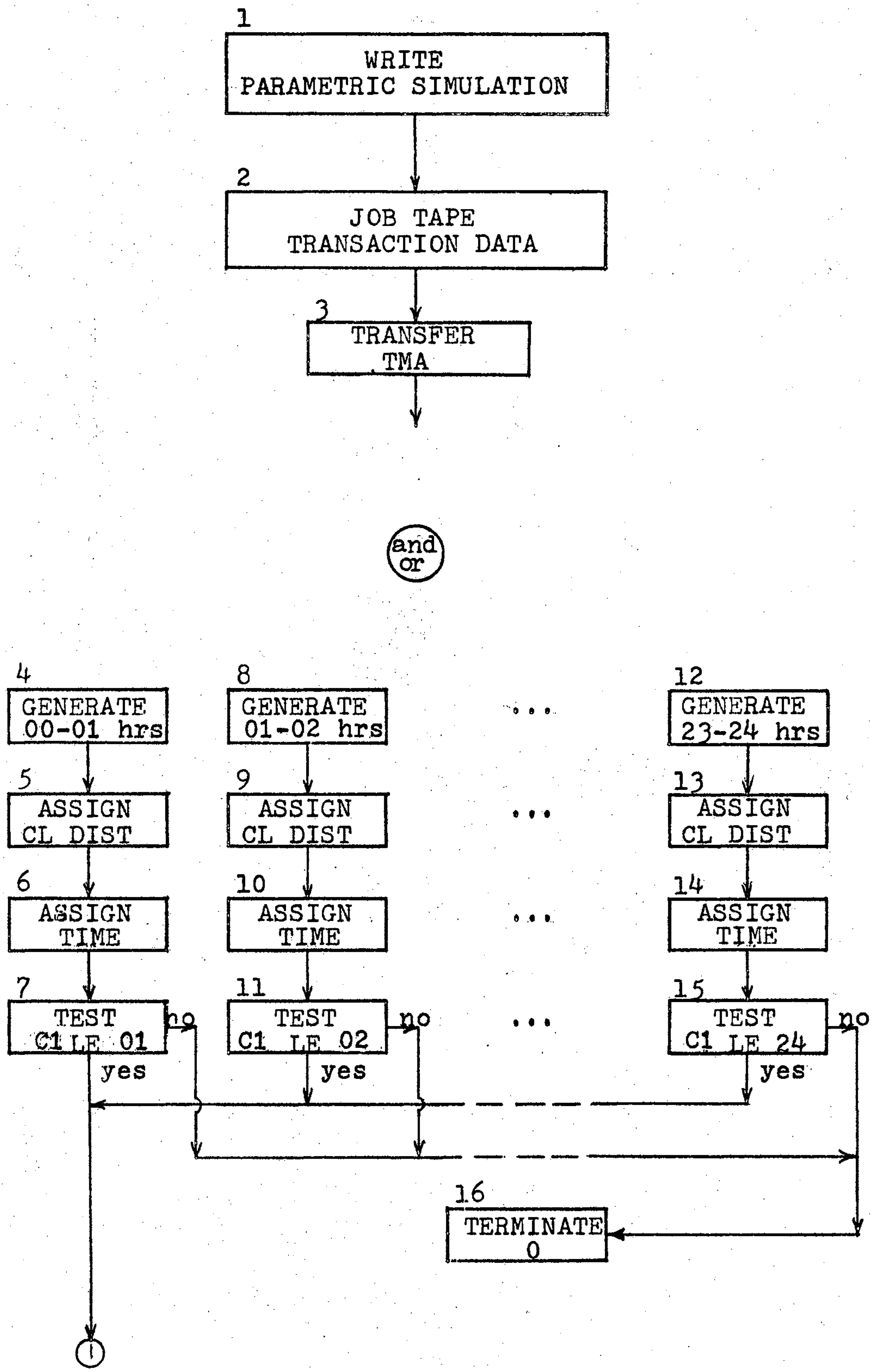
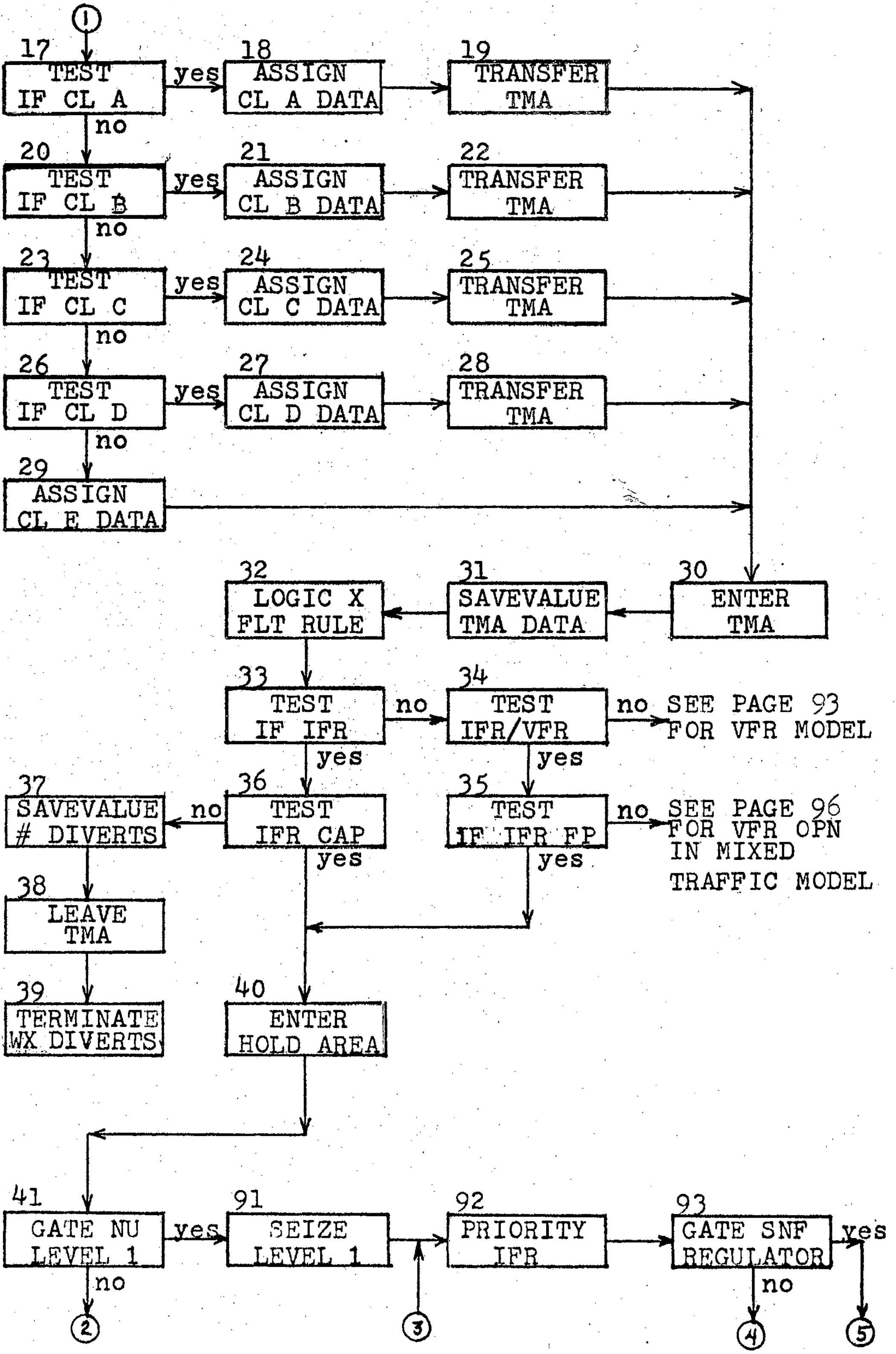


Figure 9. Flow Chart for Comprehensive Airport Systems Simulation Procedure



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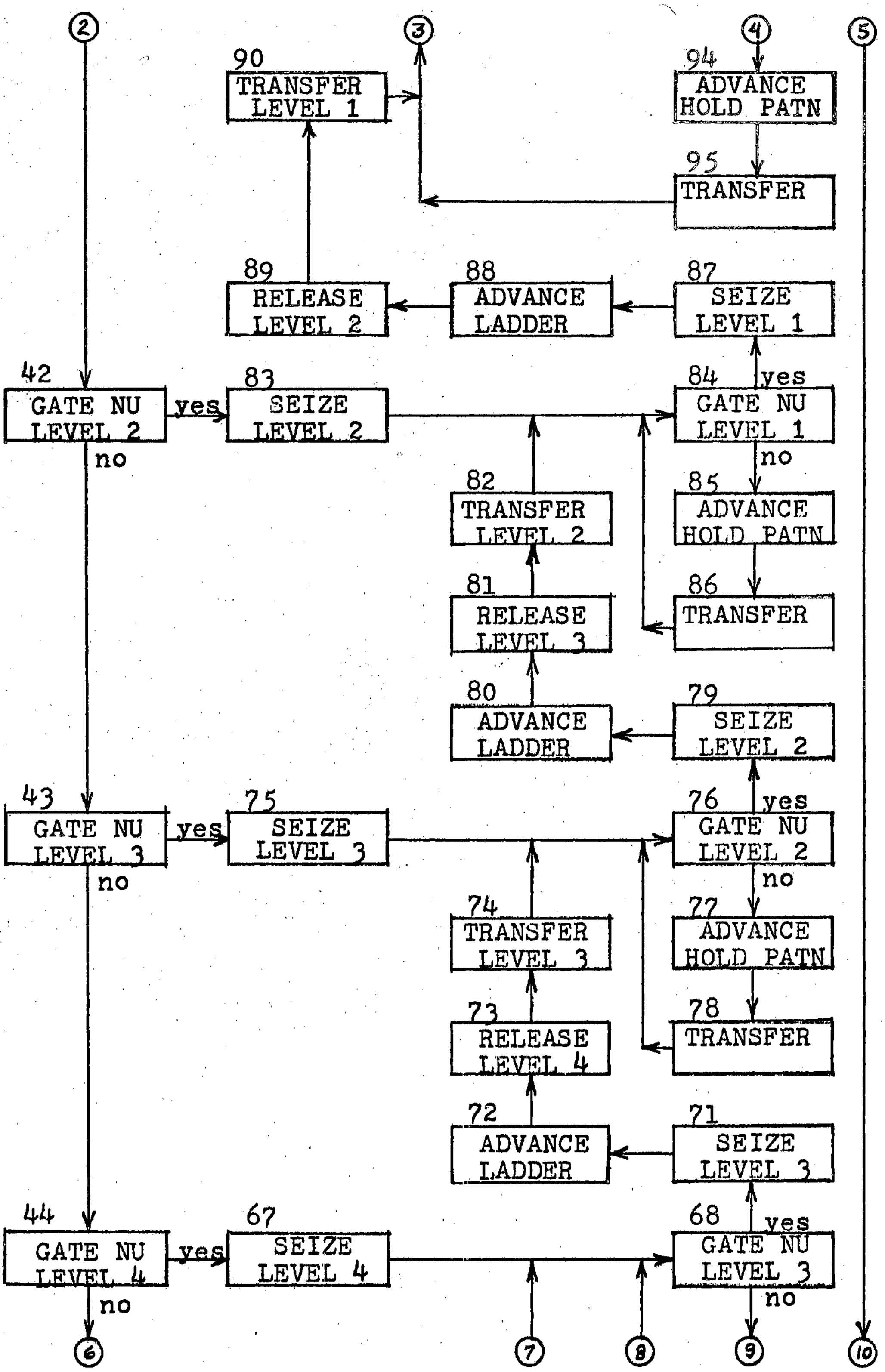

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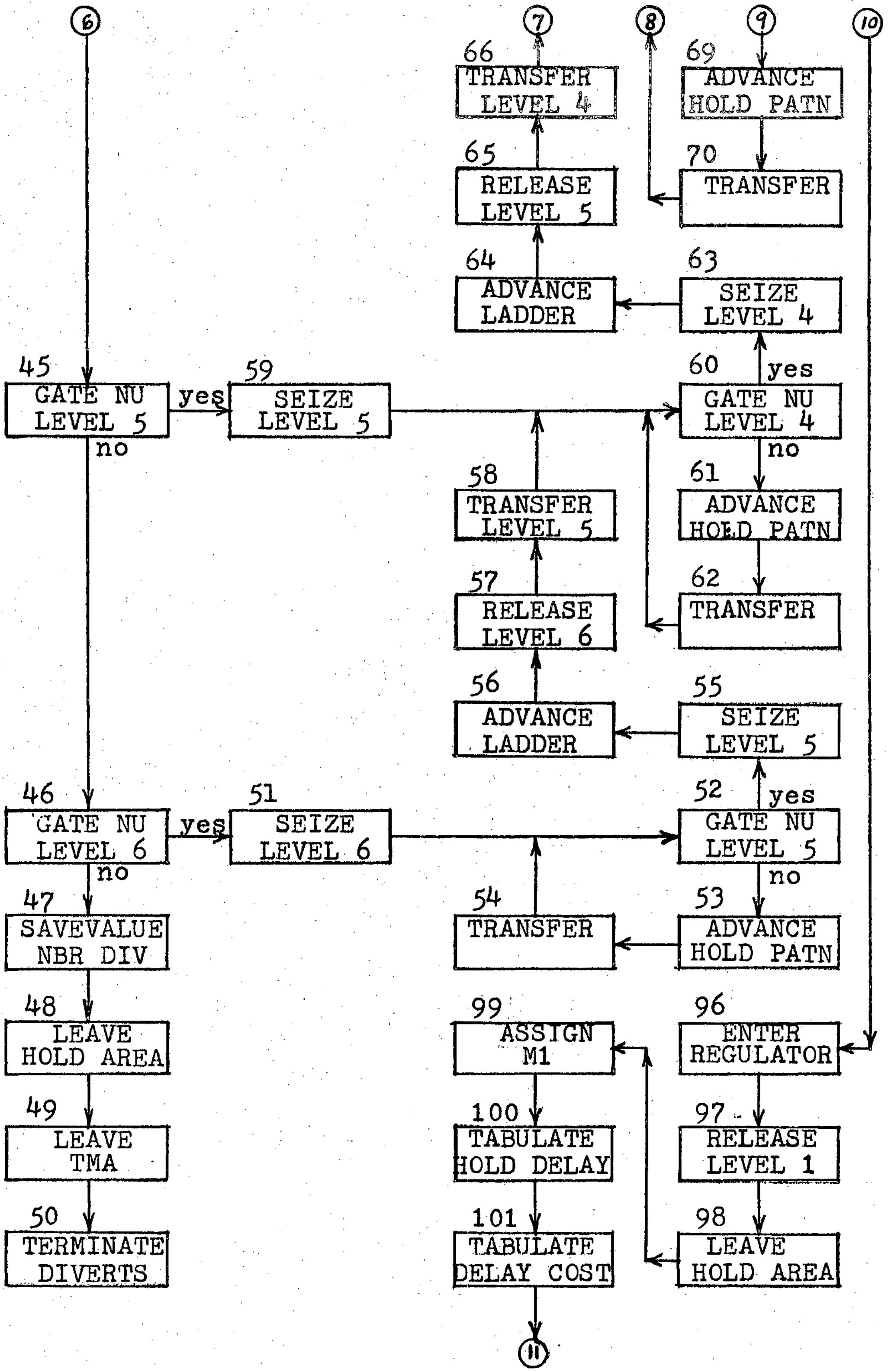

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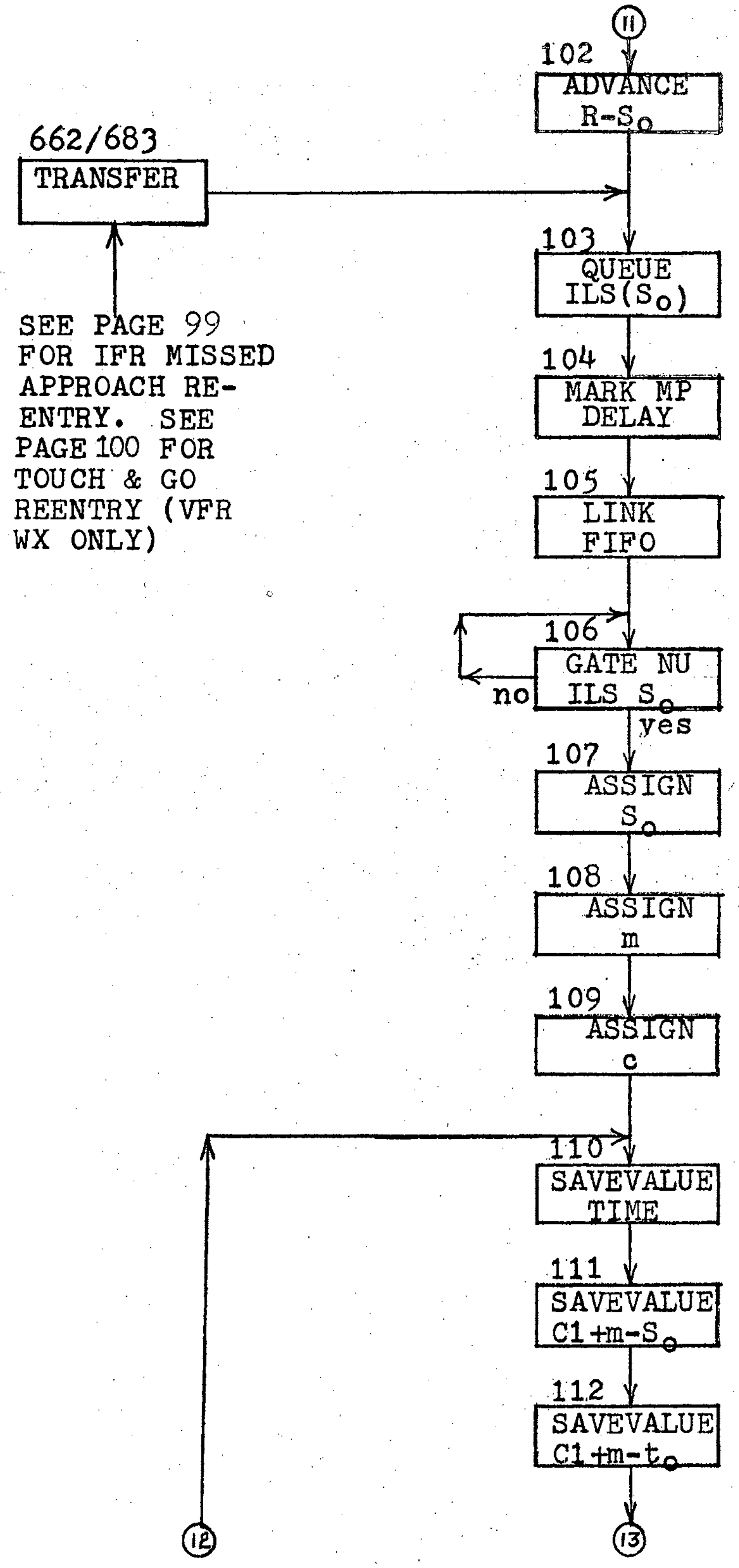
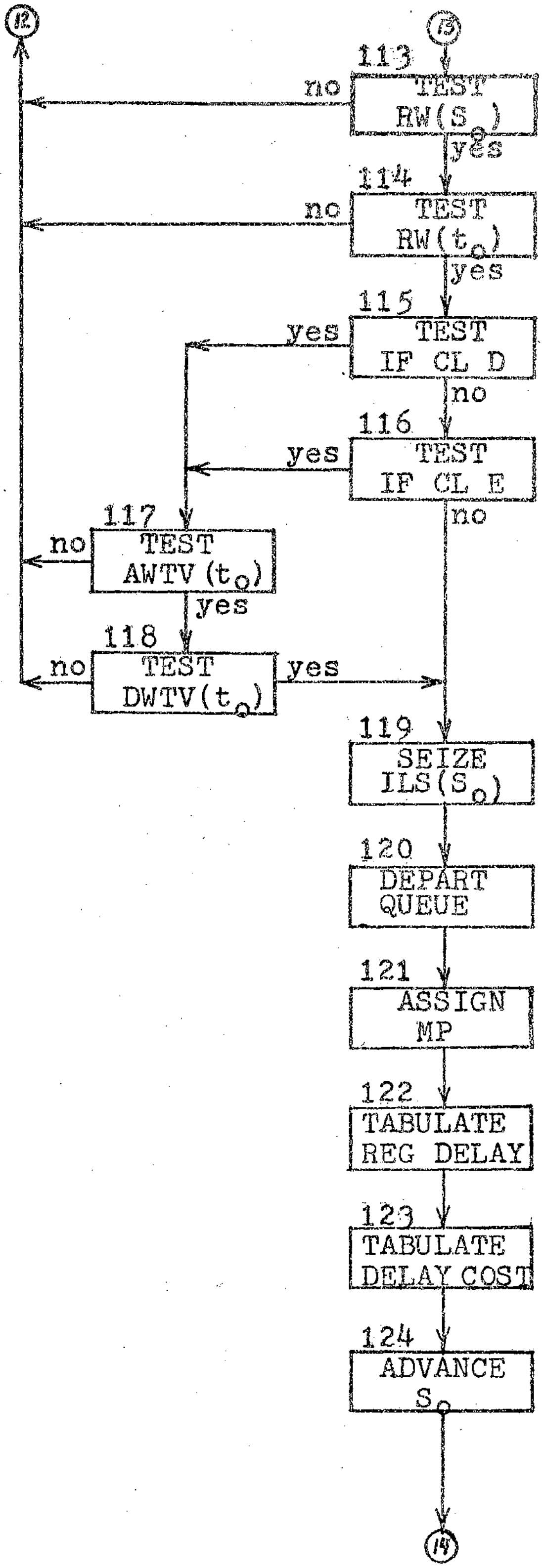


SEE PAGE 99 FOR IFR MISSED APPROACH RE-ENTRY. SEE PAGE 100 FOR TOUCH & GO REENTRY (VFR WX ONLY)

Figure 9. (Continued)



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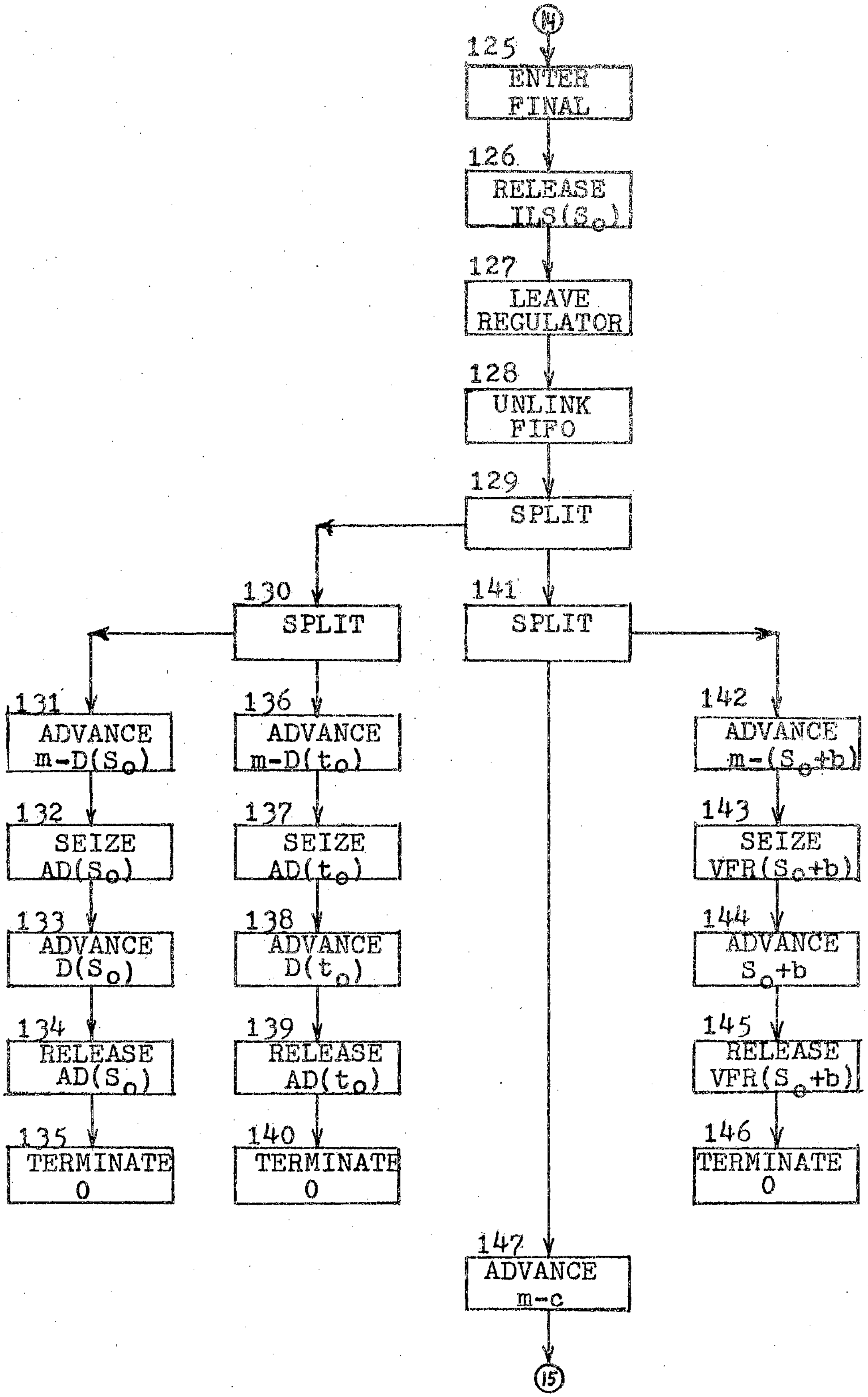

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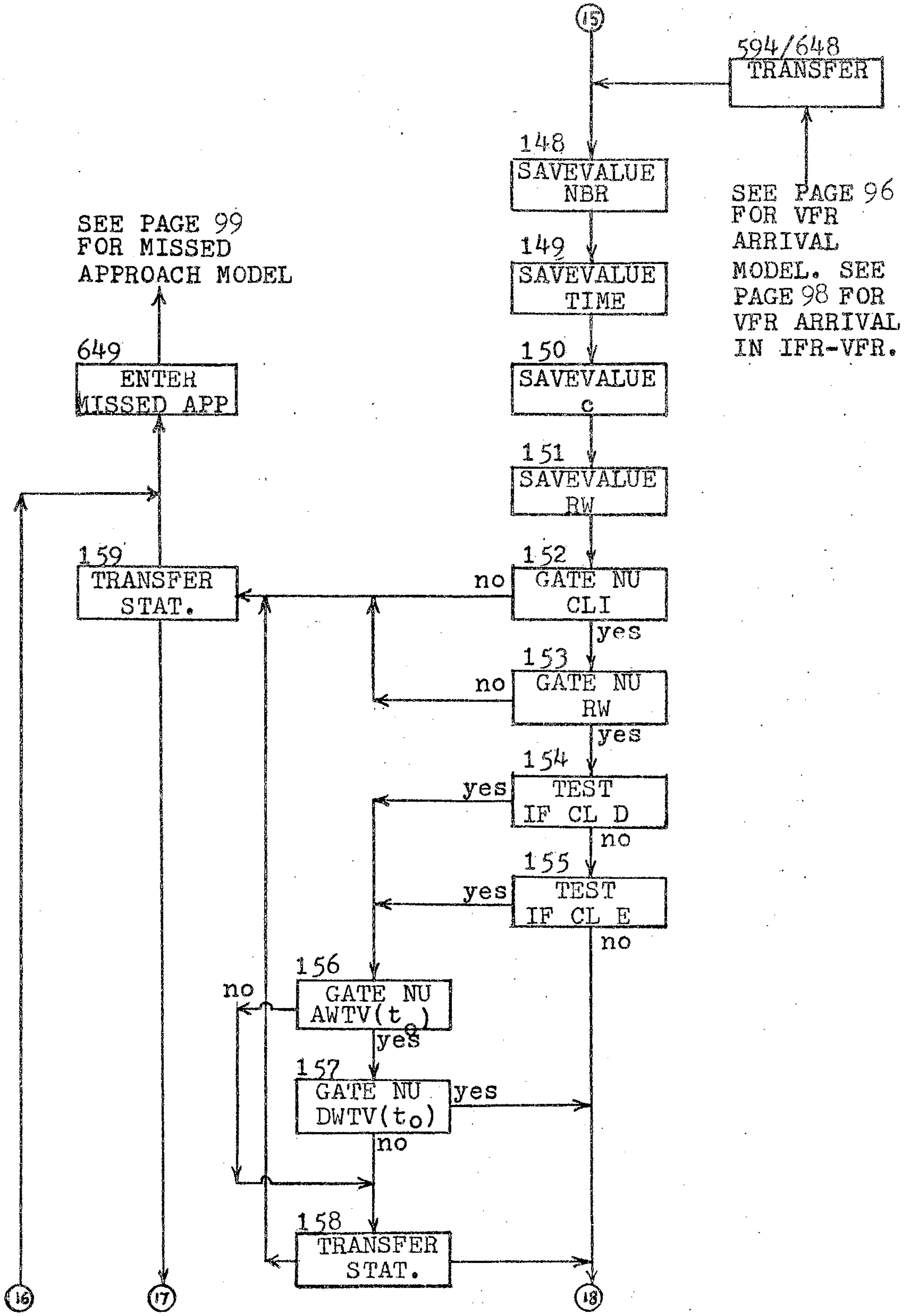

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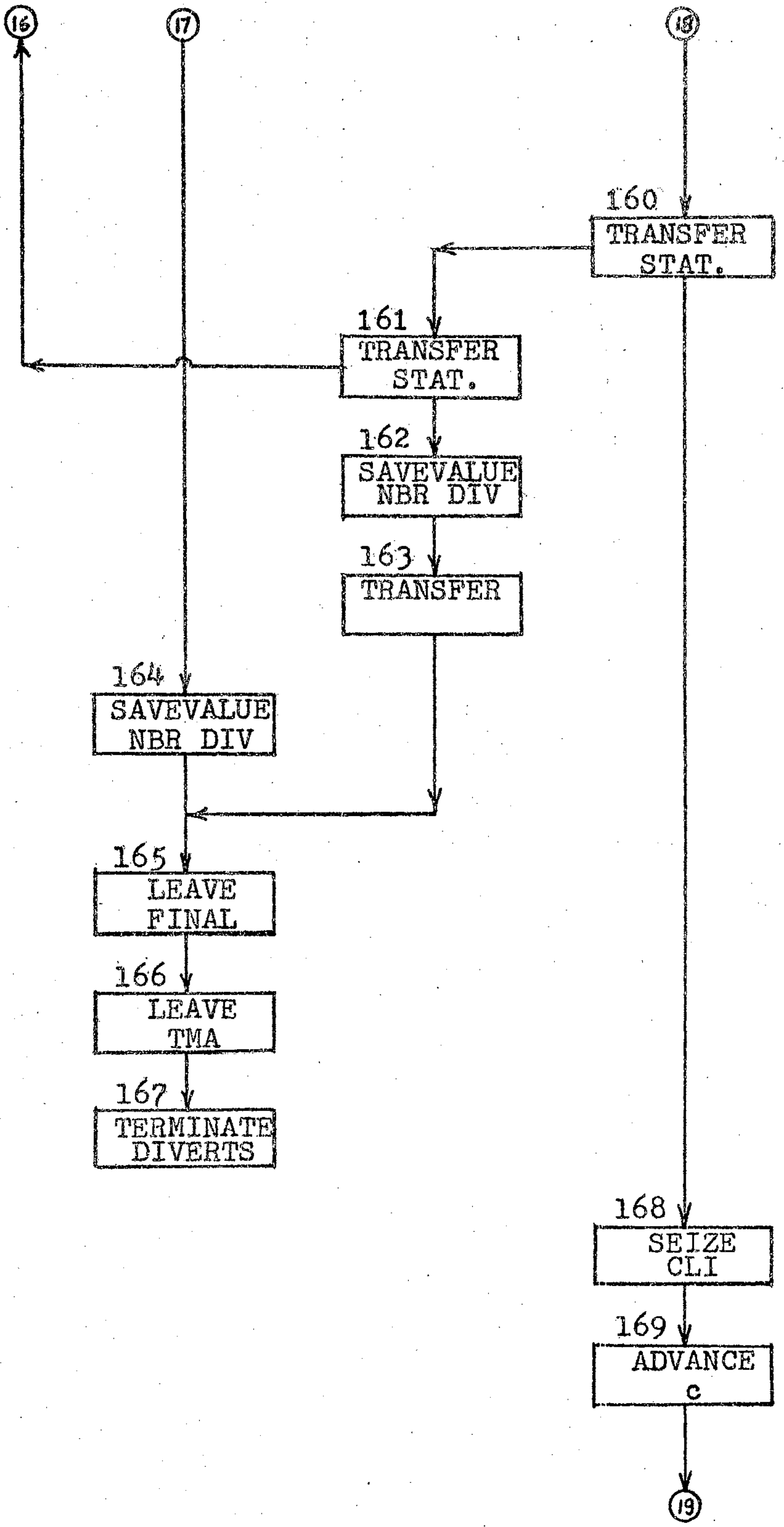

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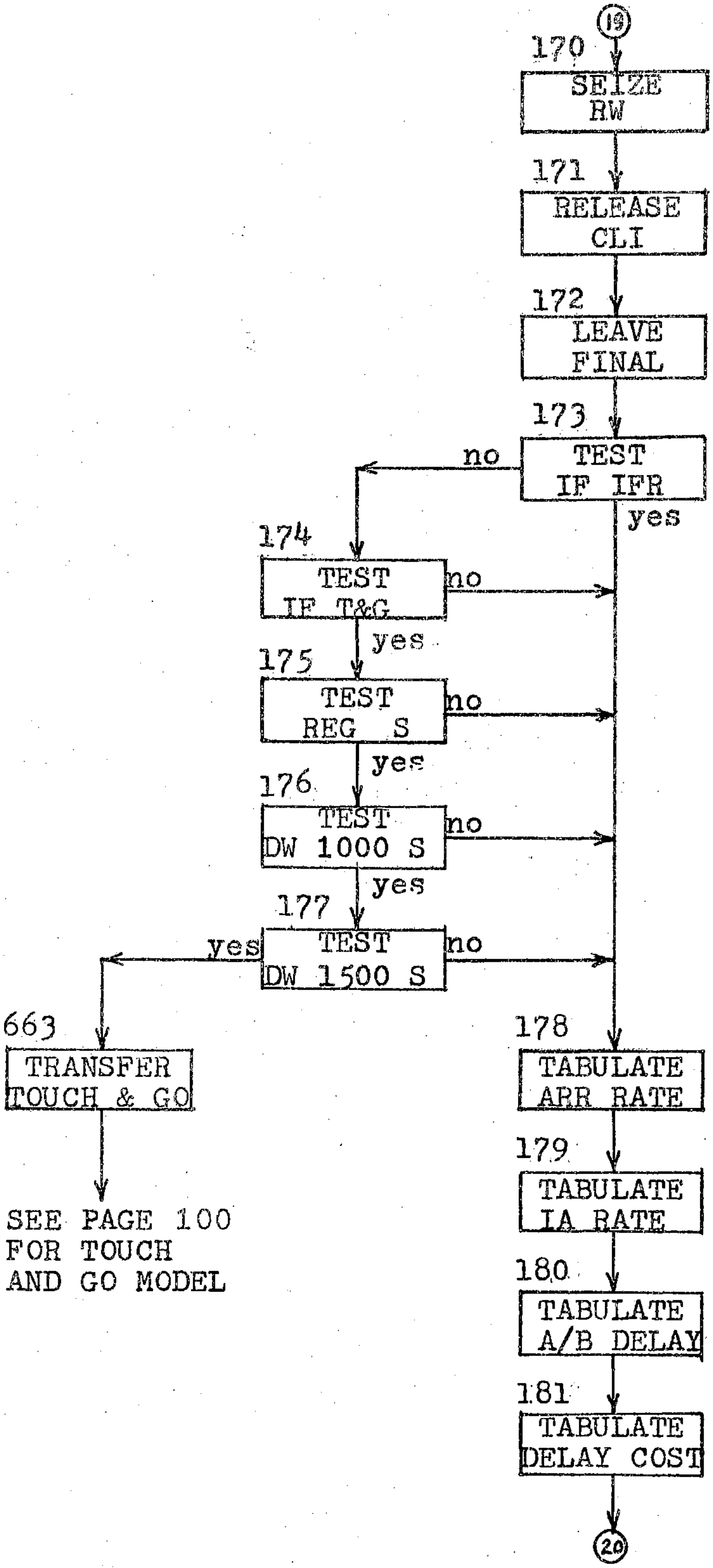

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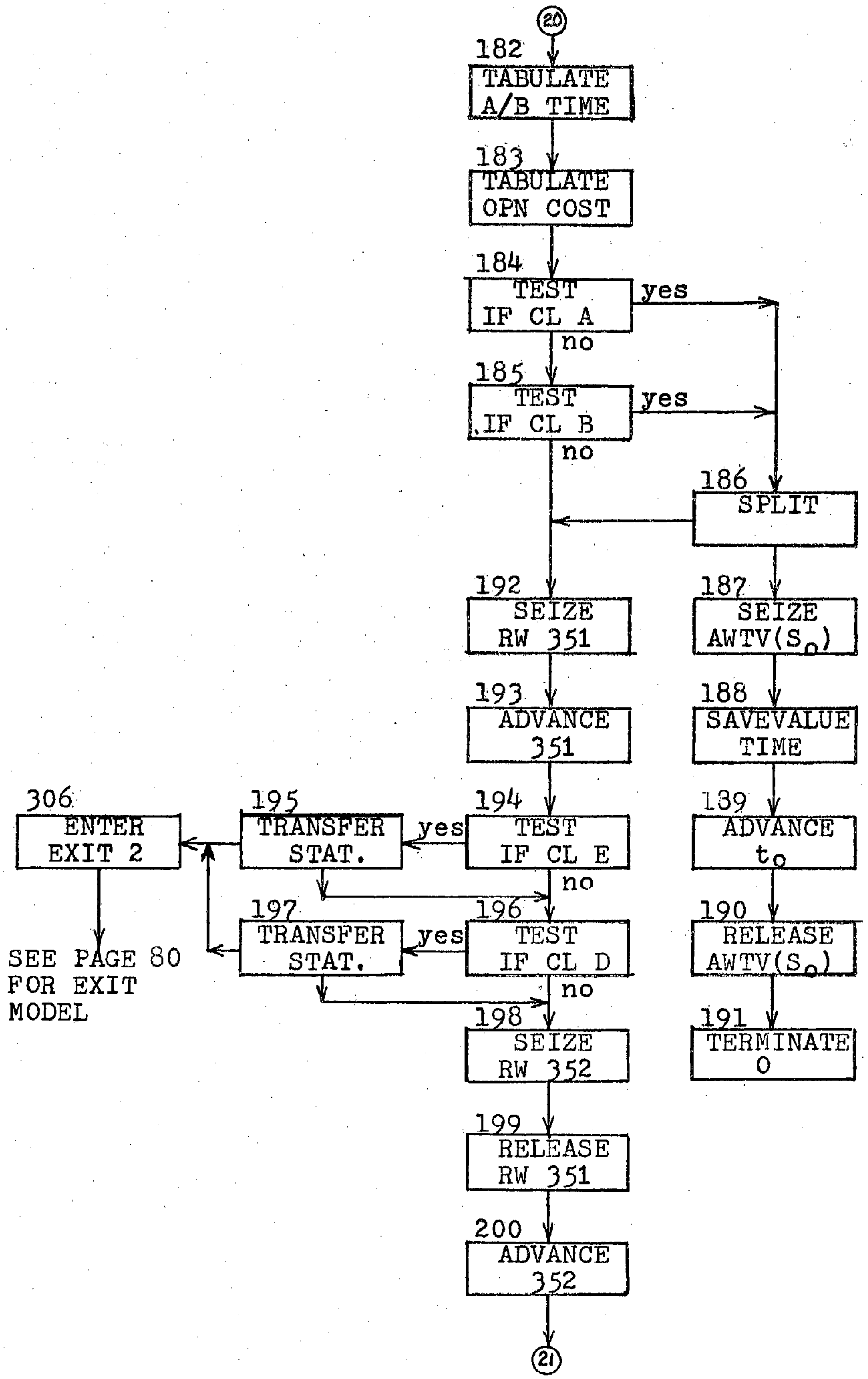

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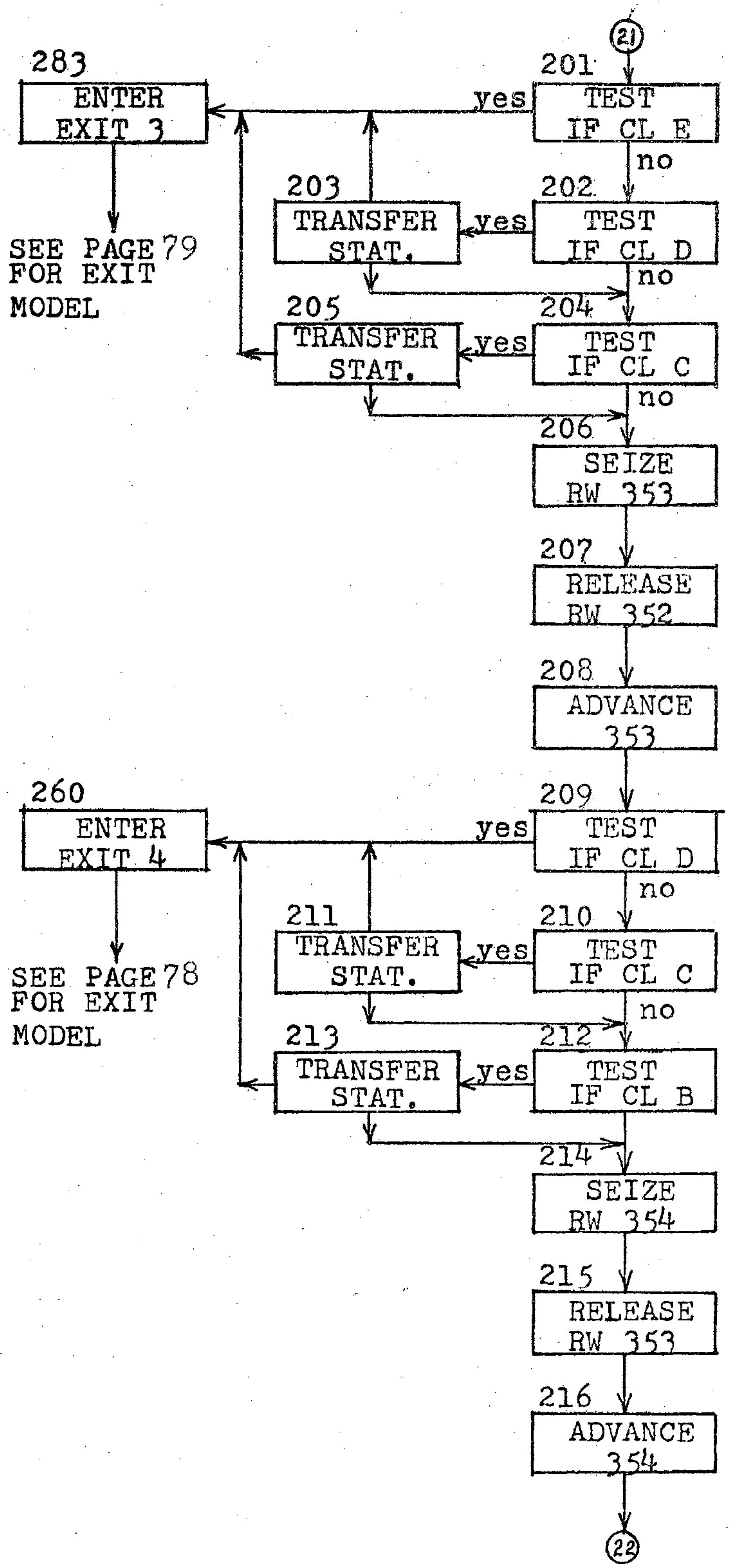

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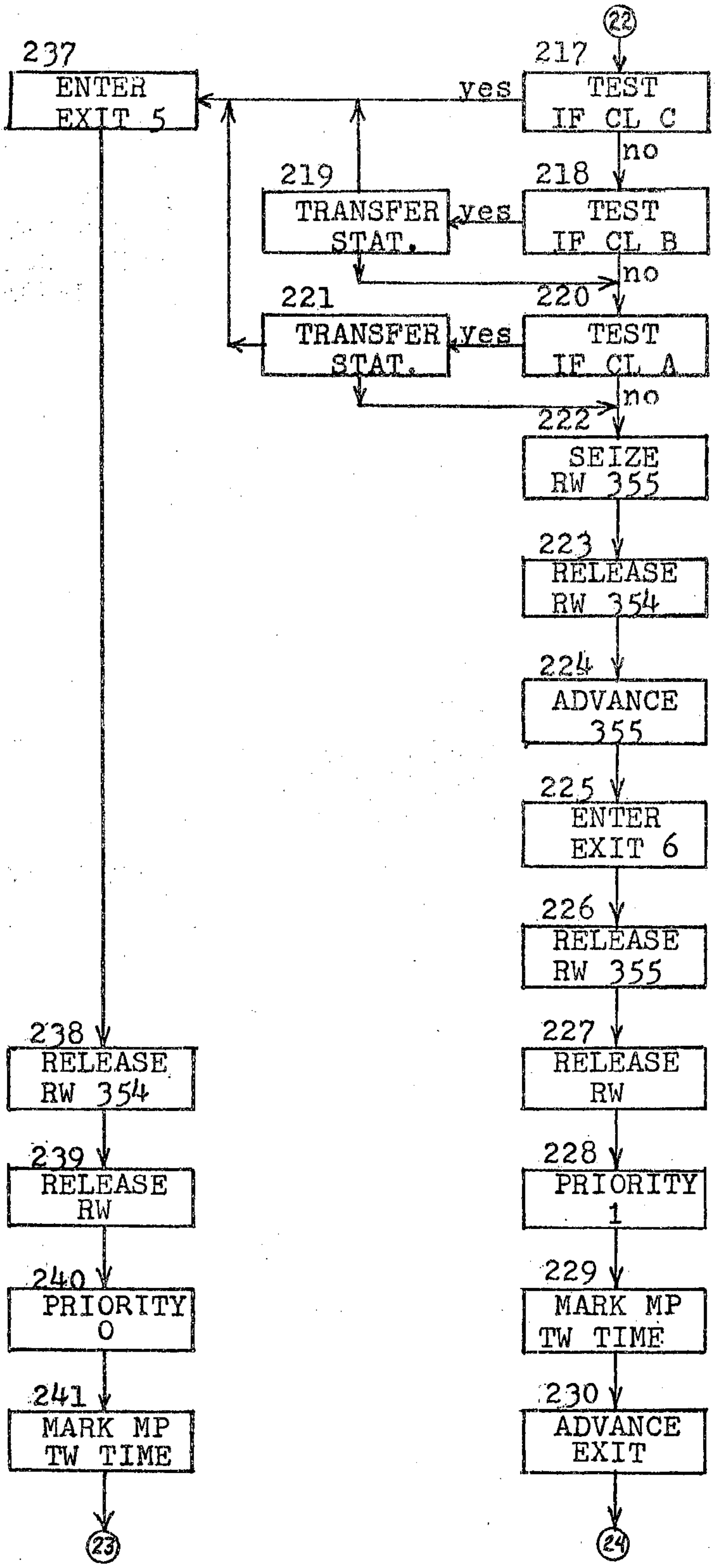

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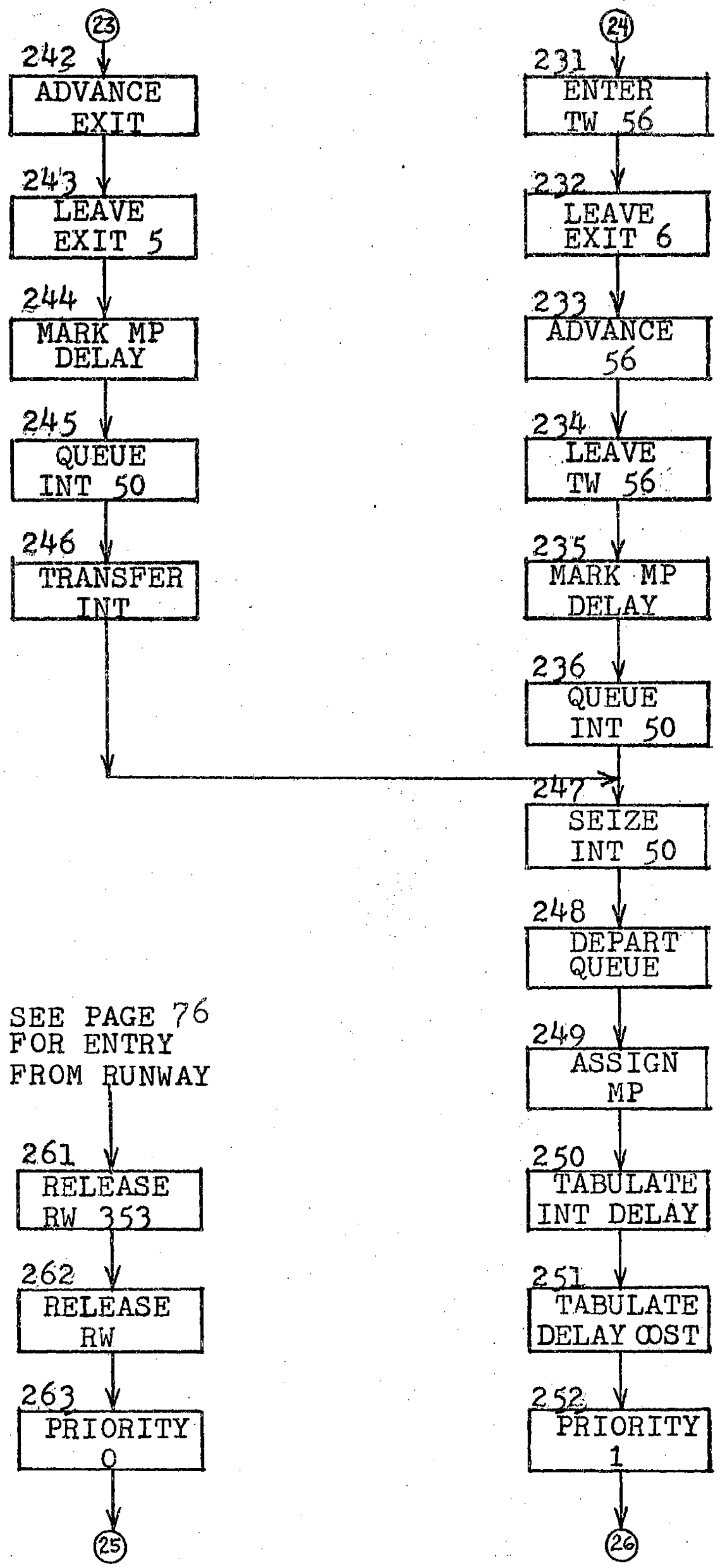

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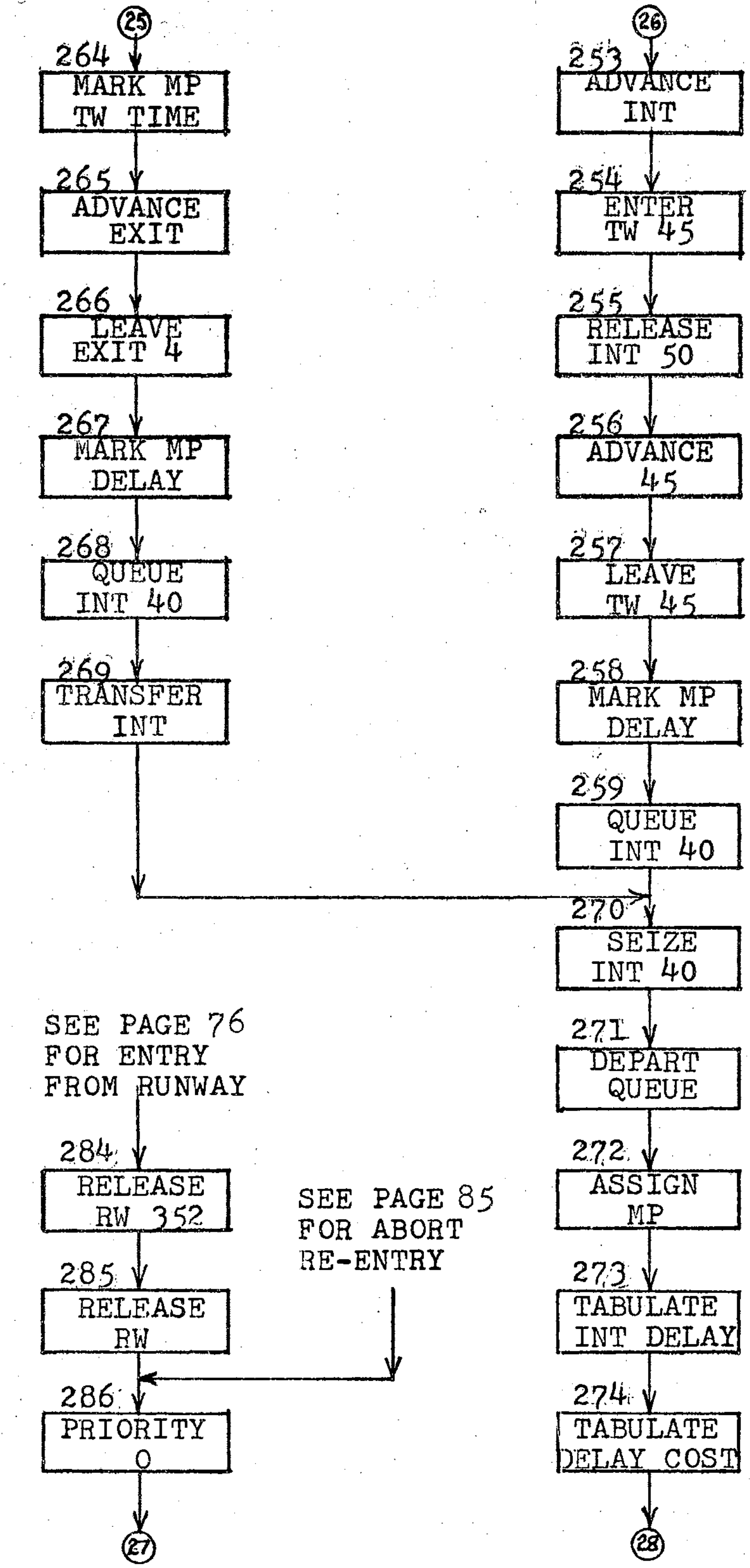

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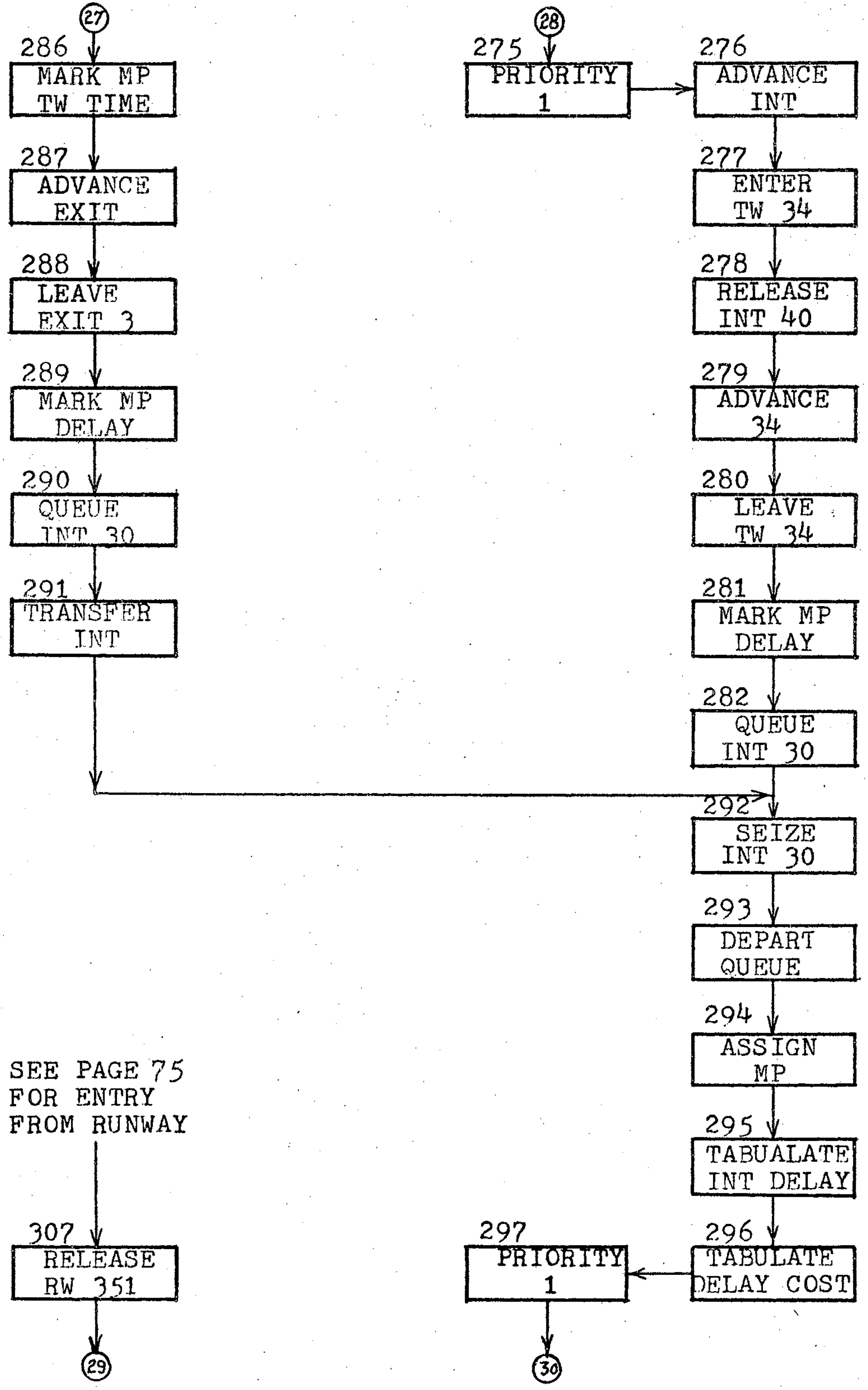

SEE PAGE 75
FOR ENTRY
FROM RUNWAY

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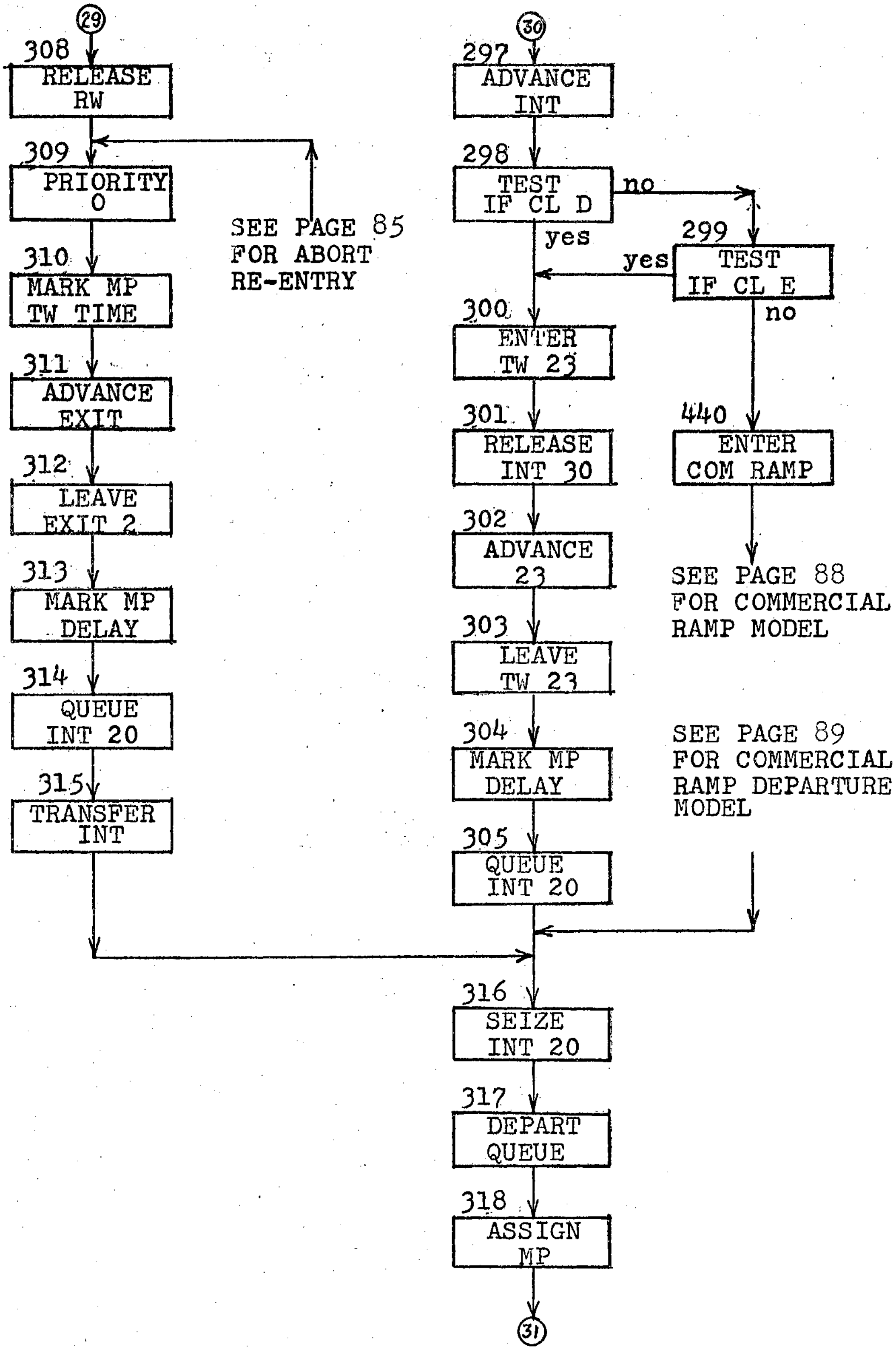

SEE PAGE 85
FOR ABORT
RE-ENTRY

SEE PAGE 88
FOR COMMERCIAL
RAMP MODEL

SEE PAGE 89
FOR COMMERCIAL
RAMP DEPARTURE
MODEL

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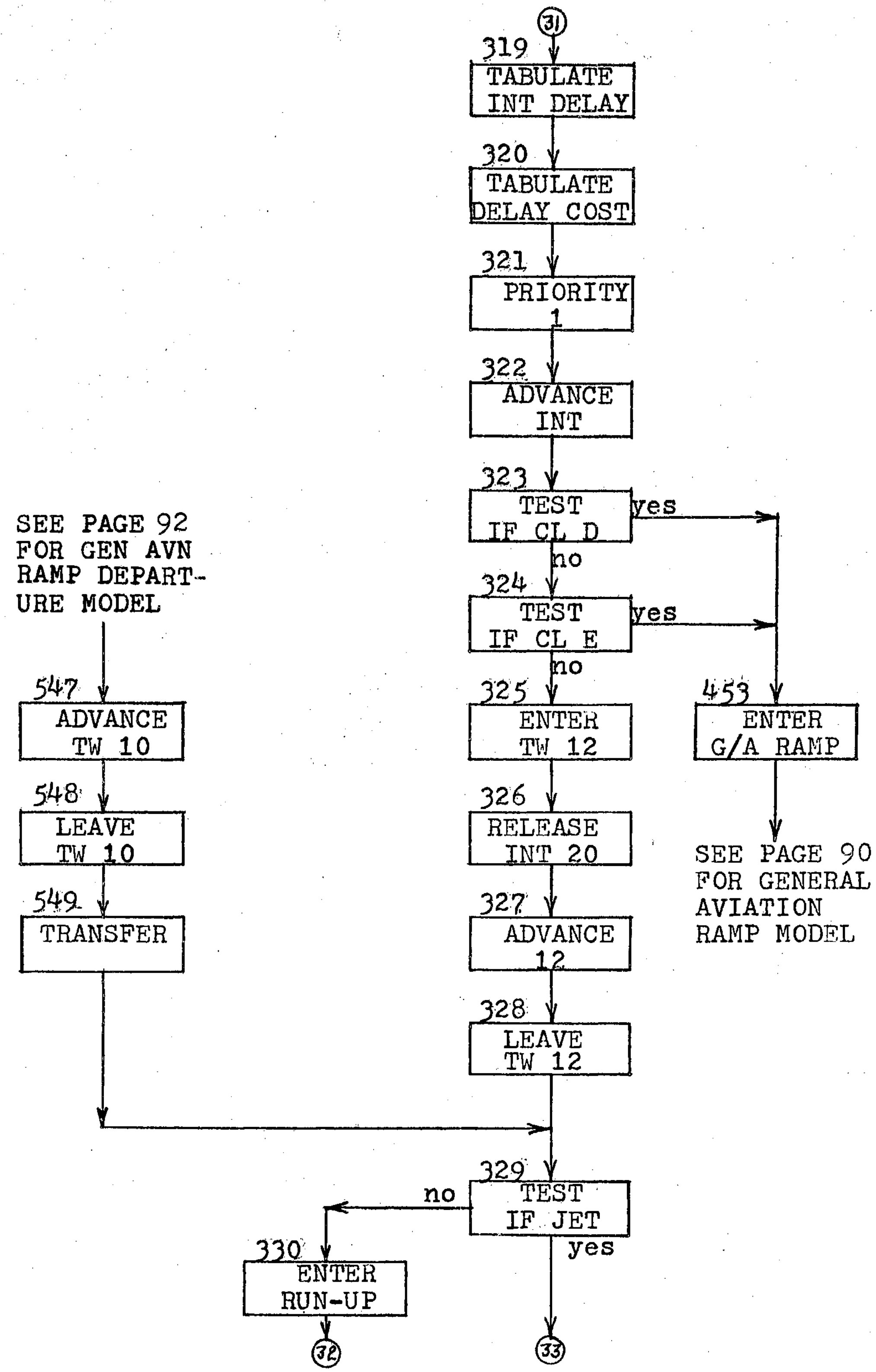

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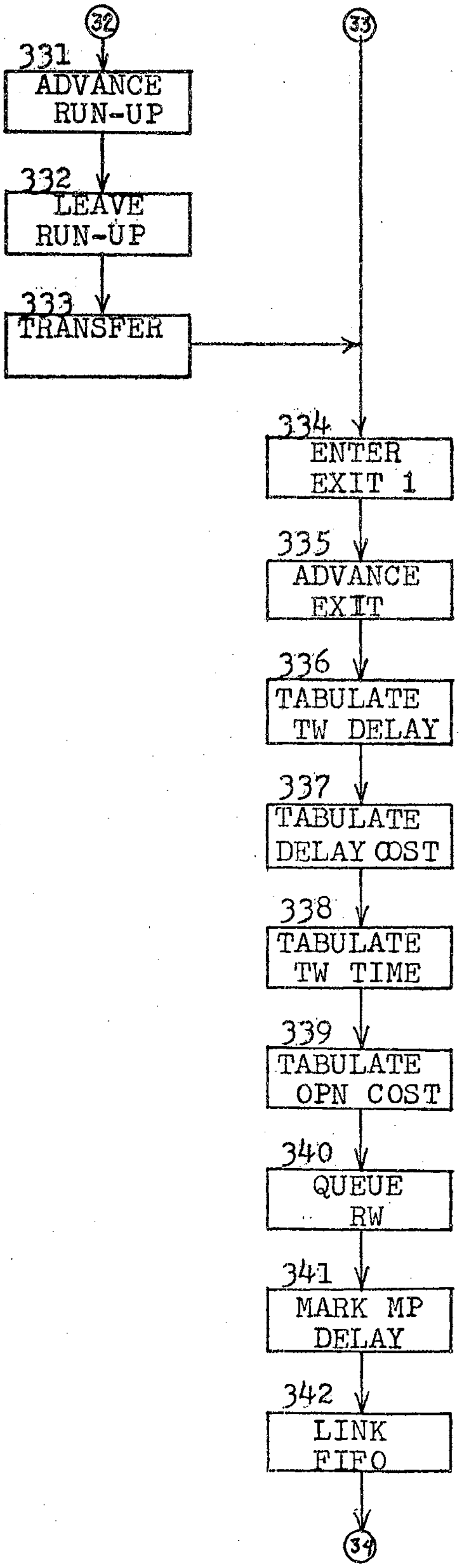

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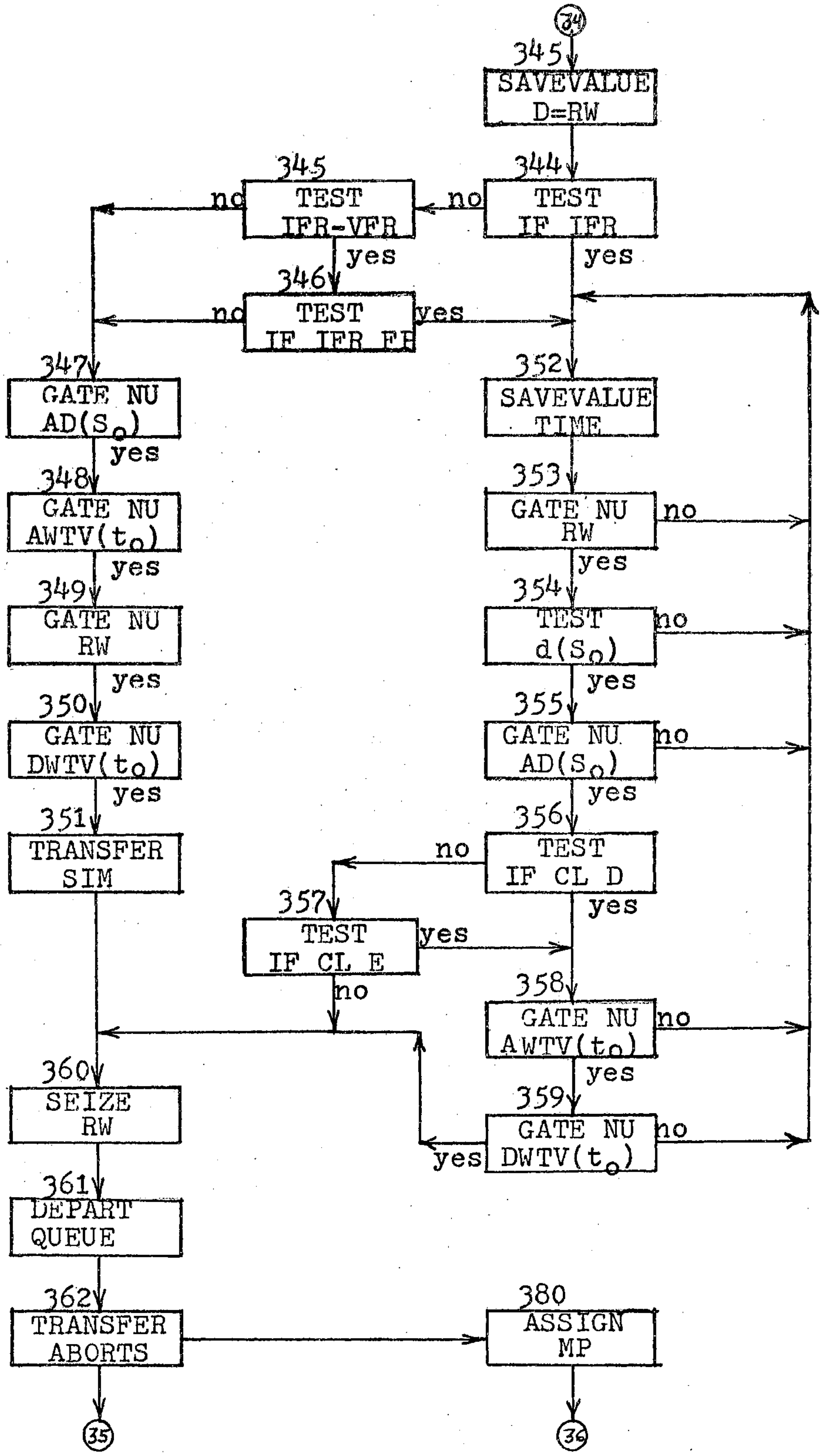

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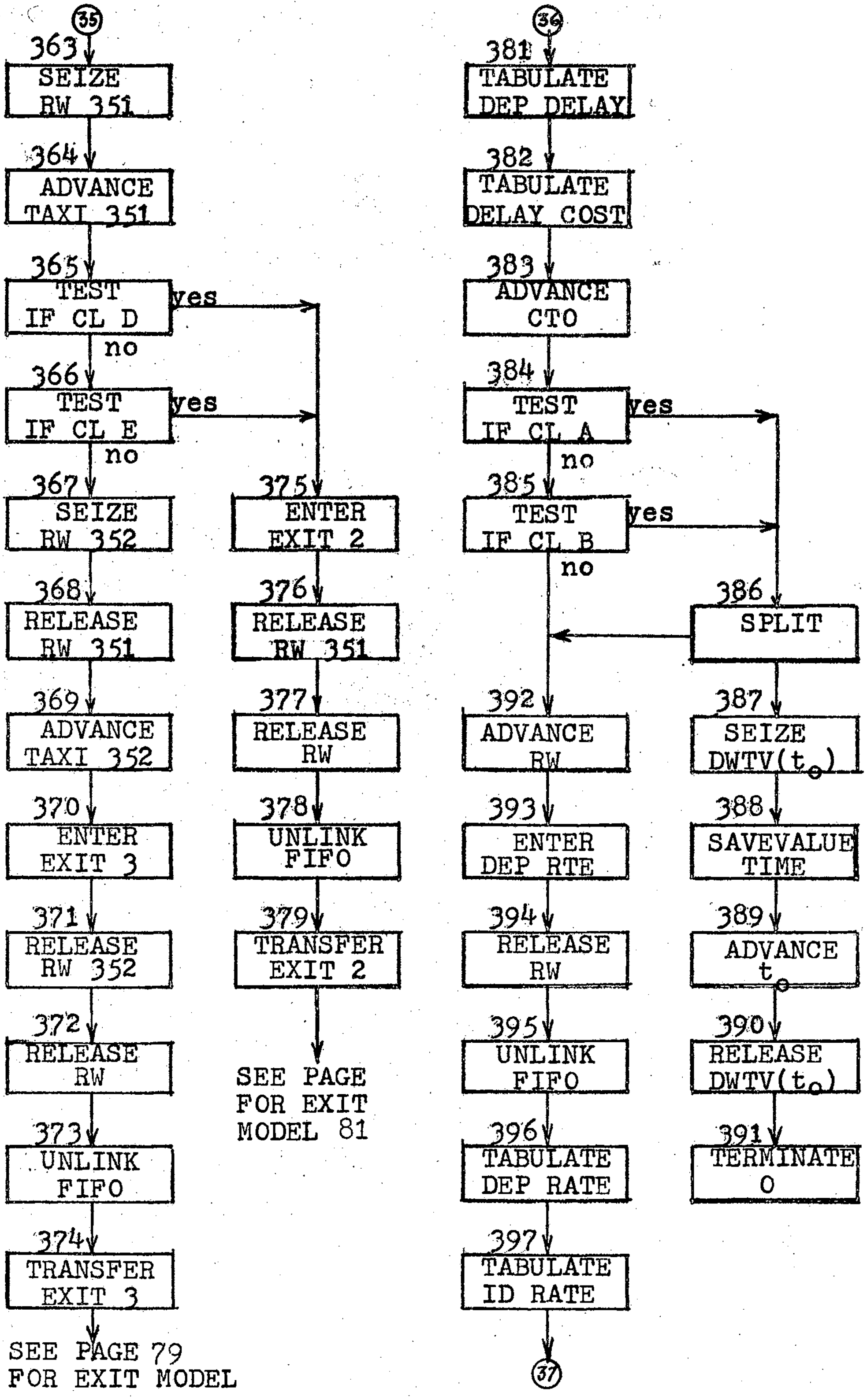

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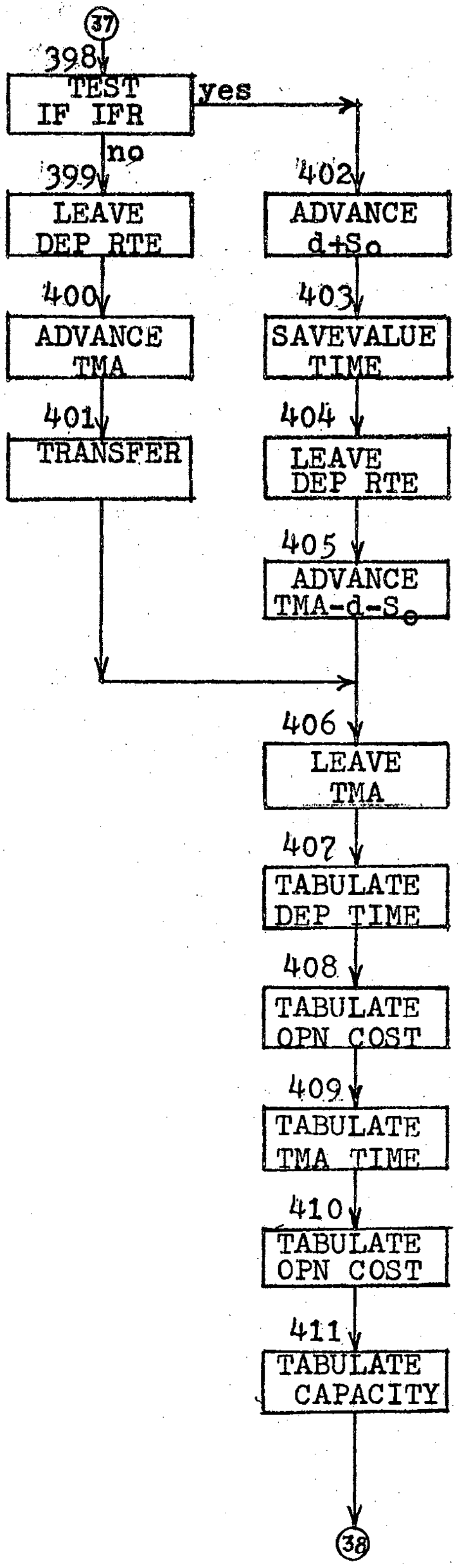

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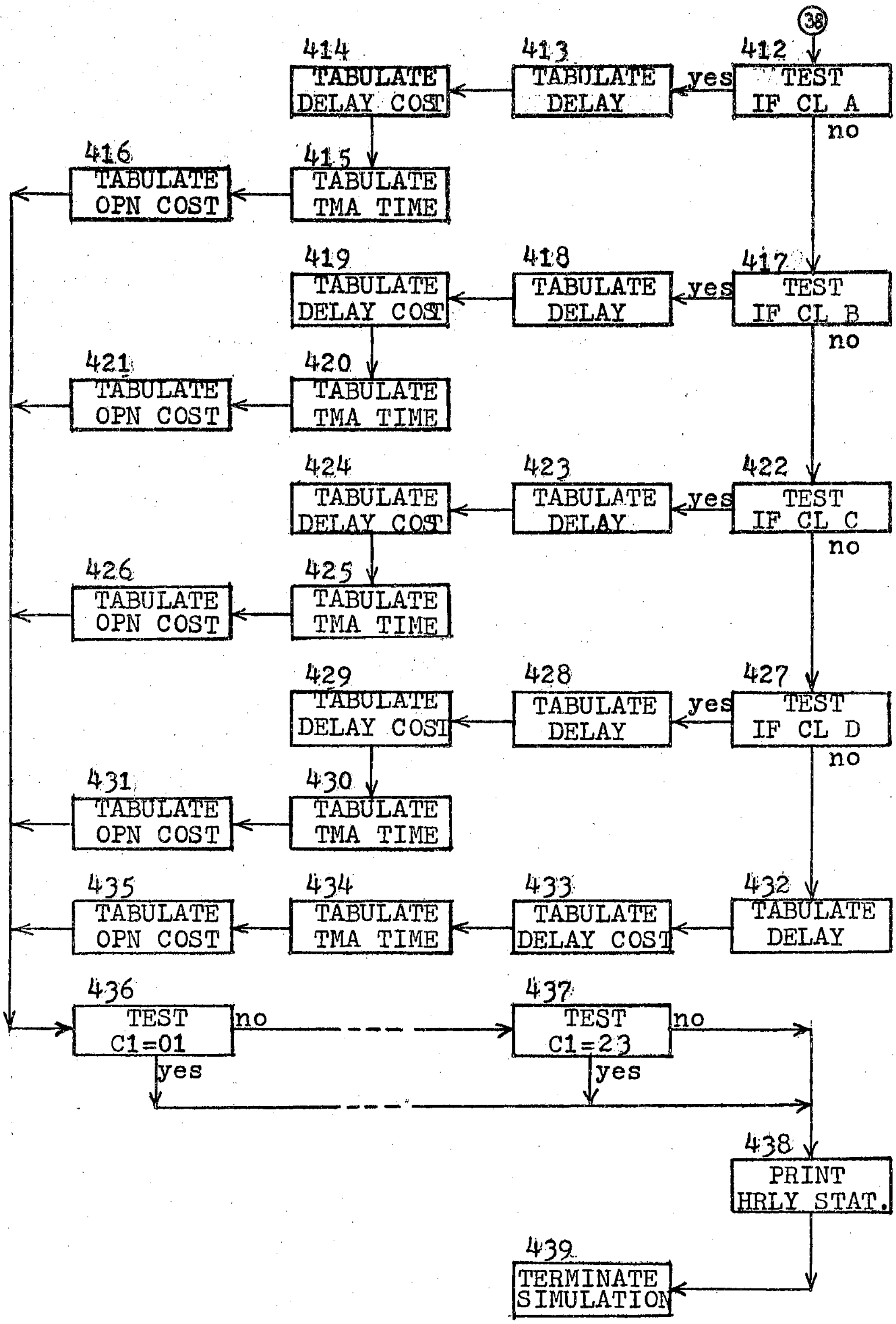

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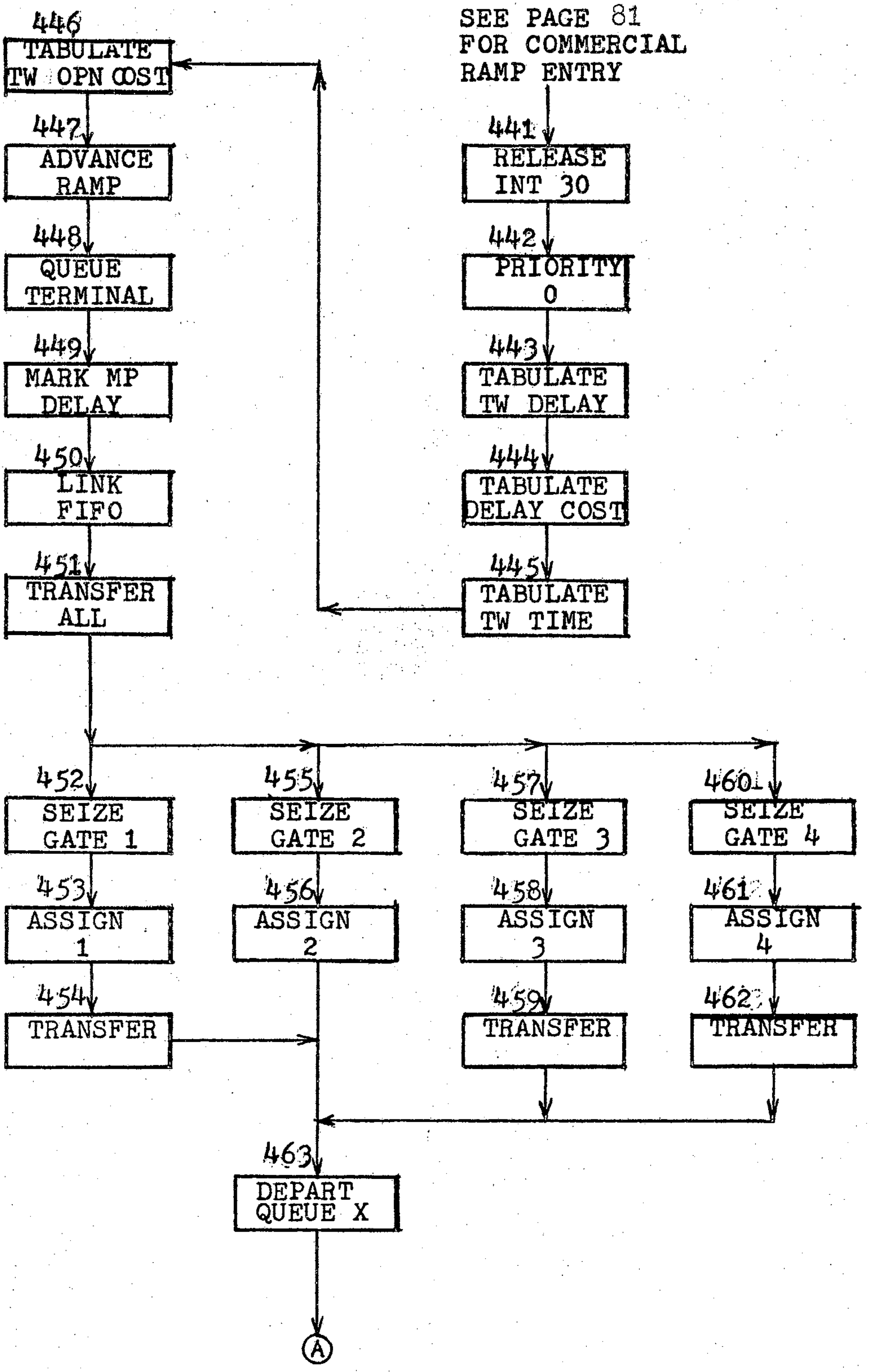

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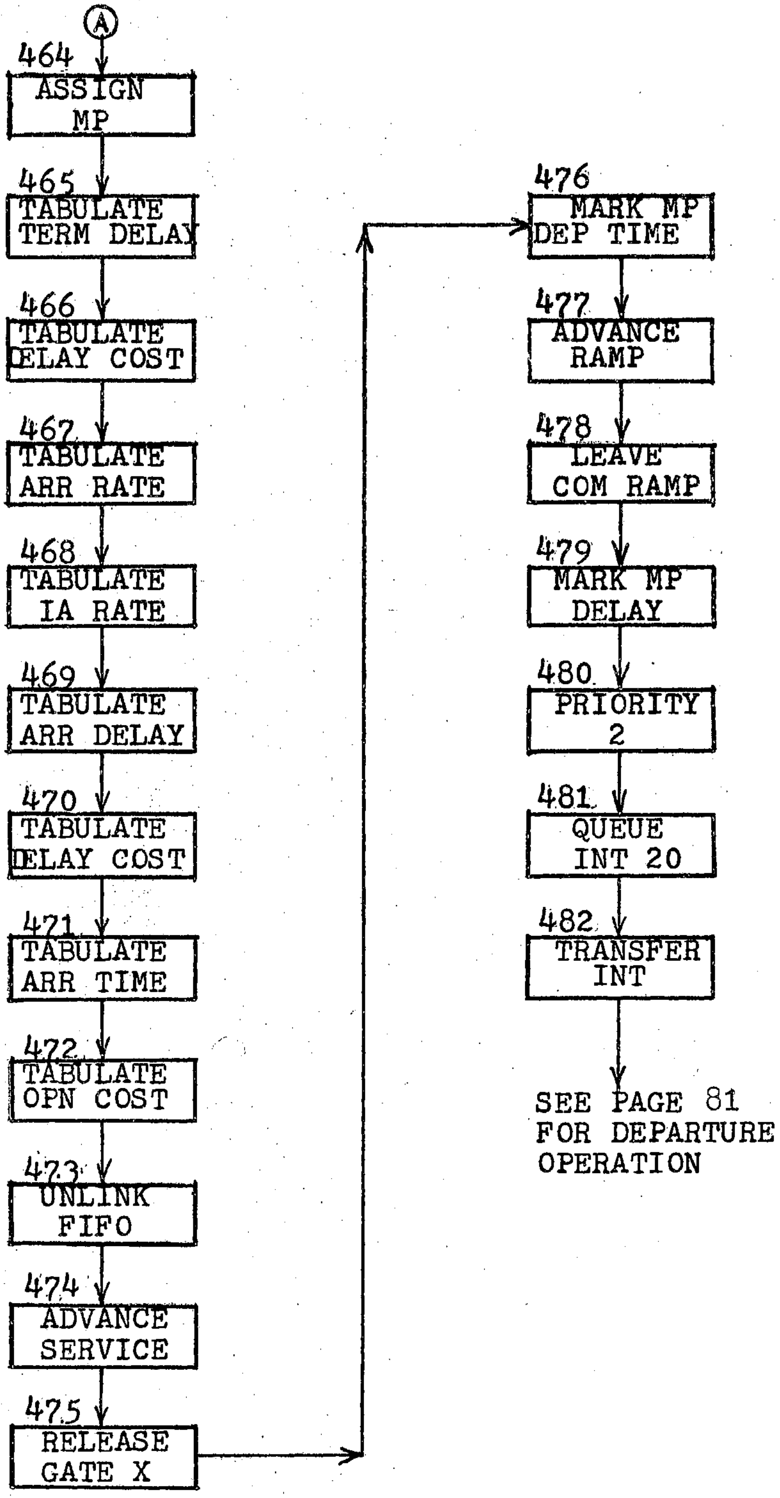

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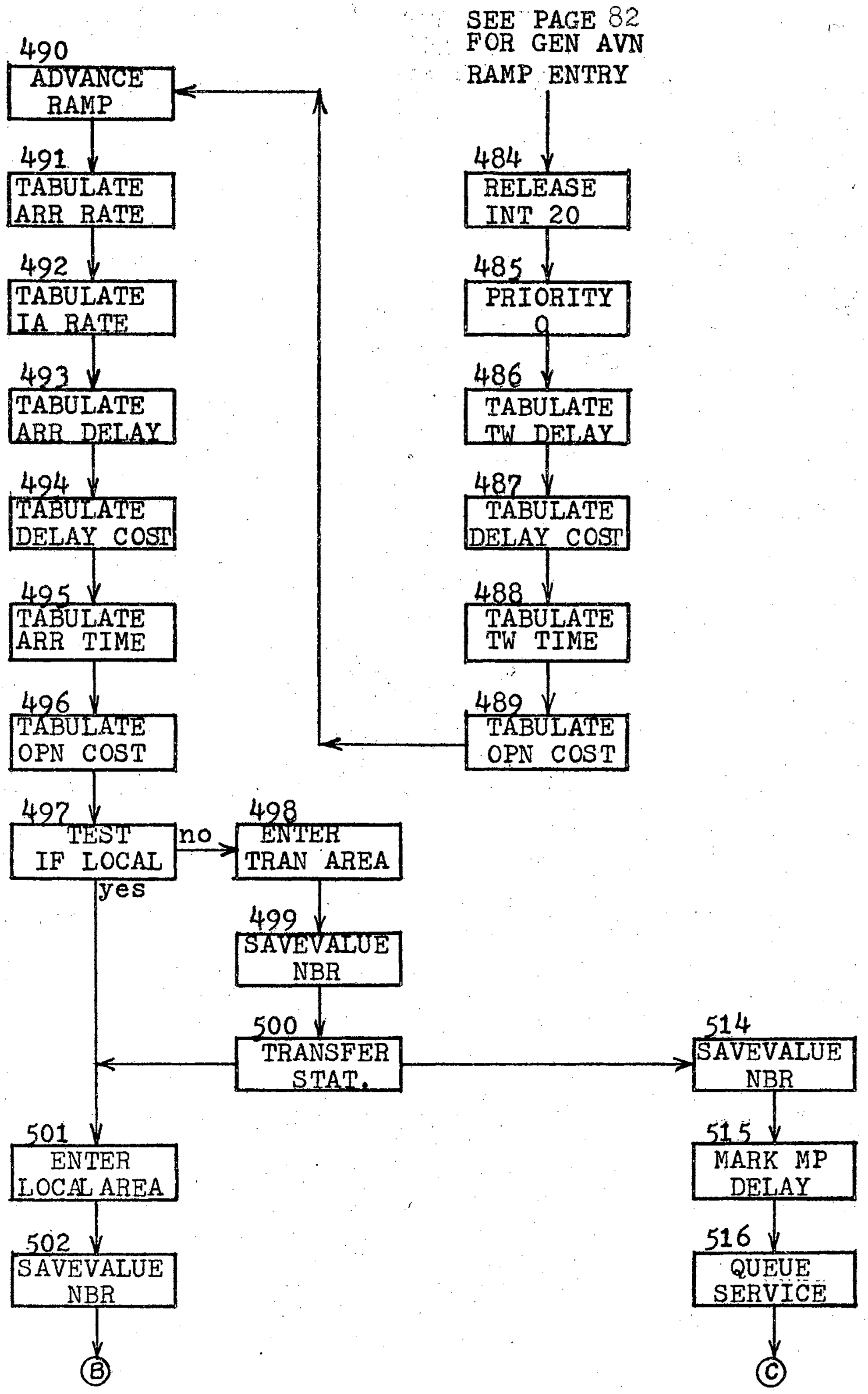

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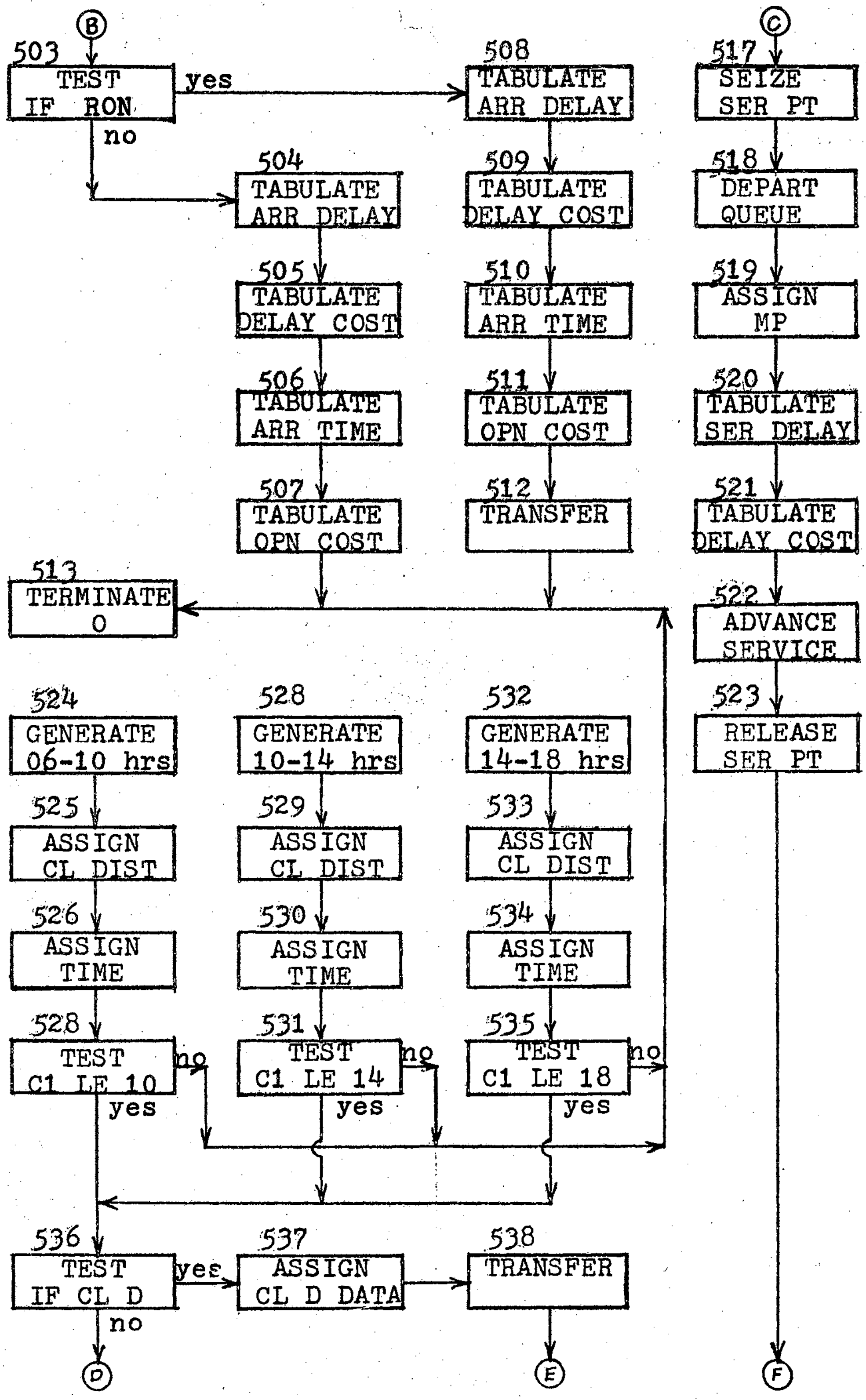

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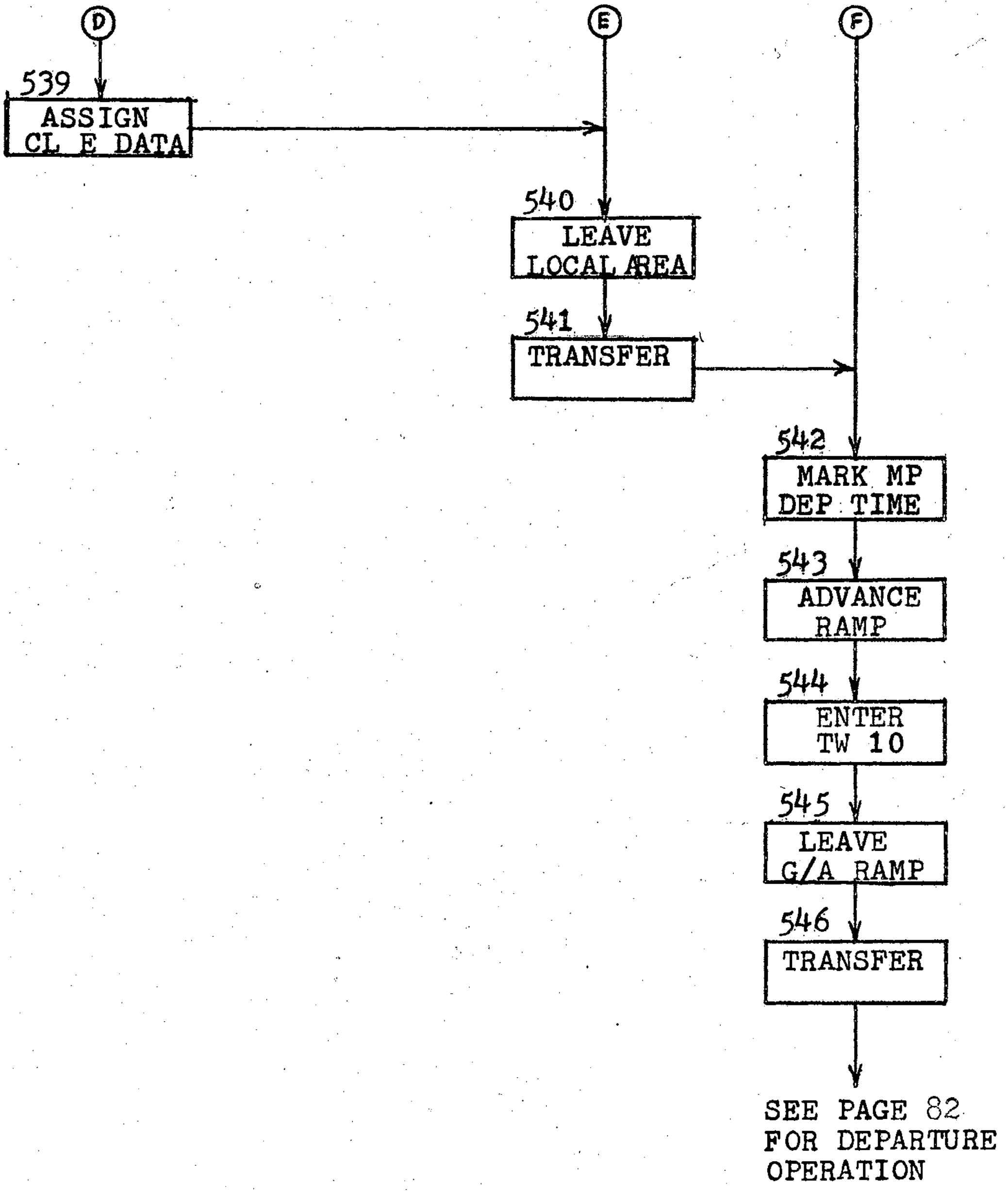

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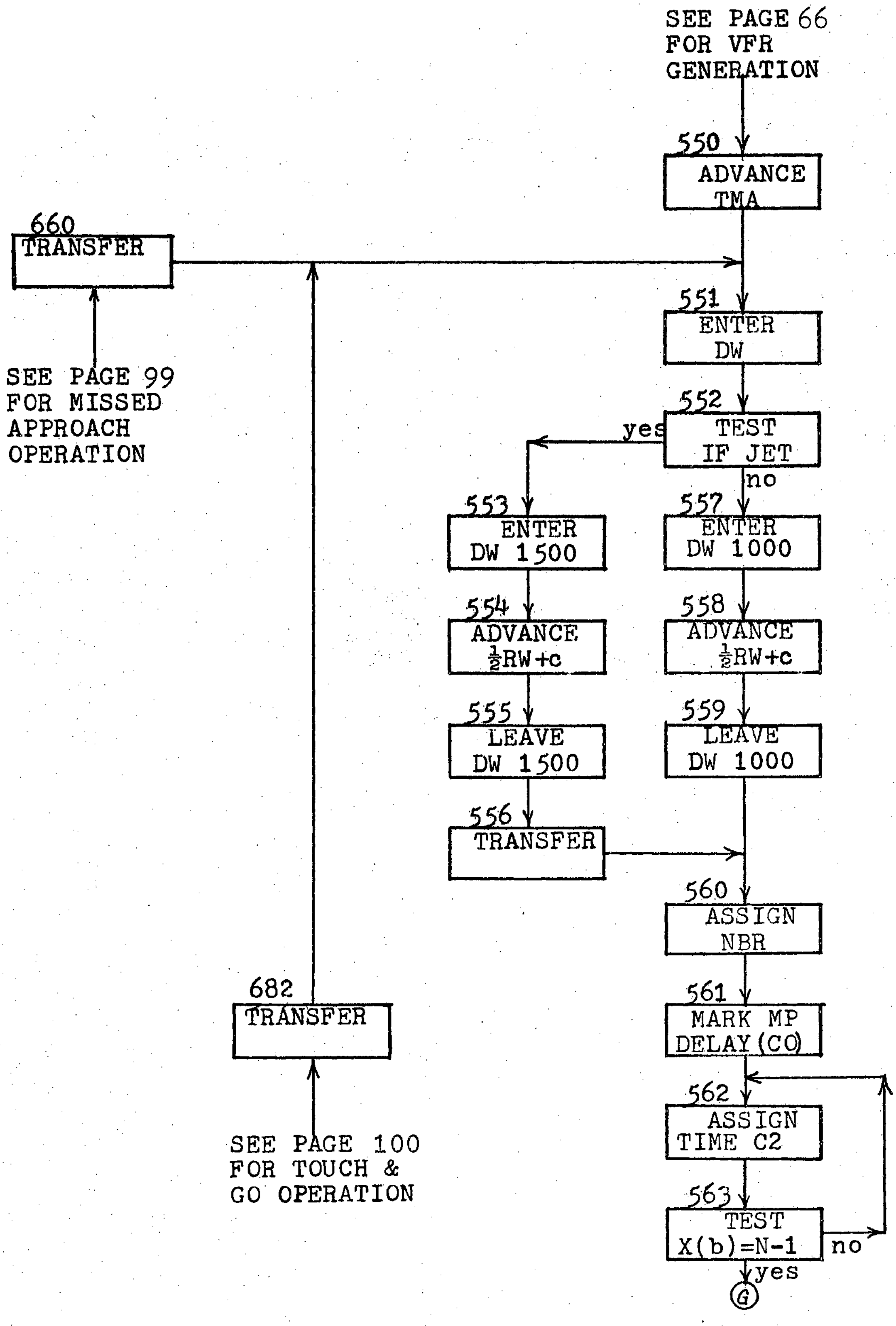

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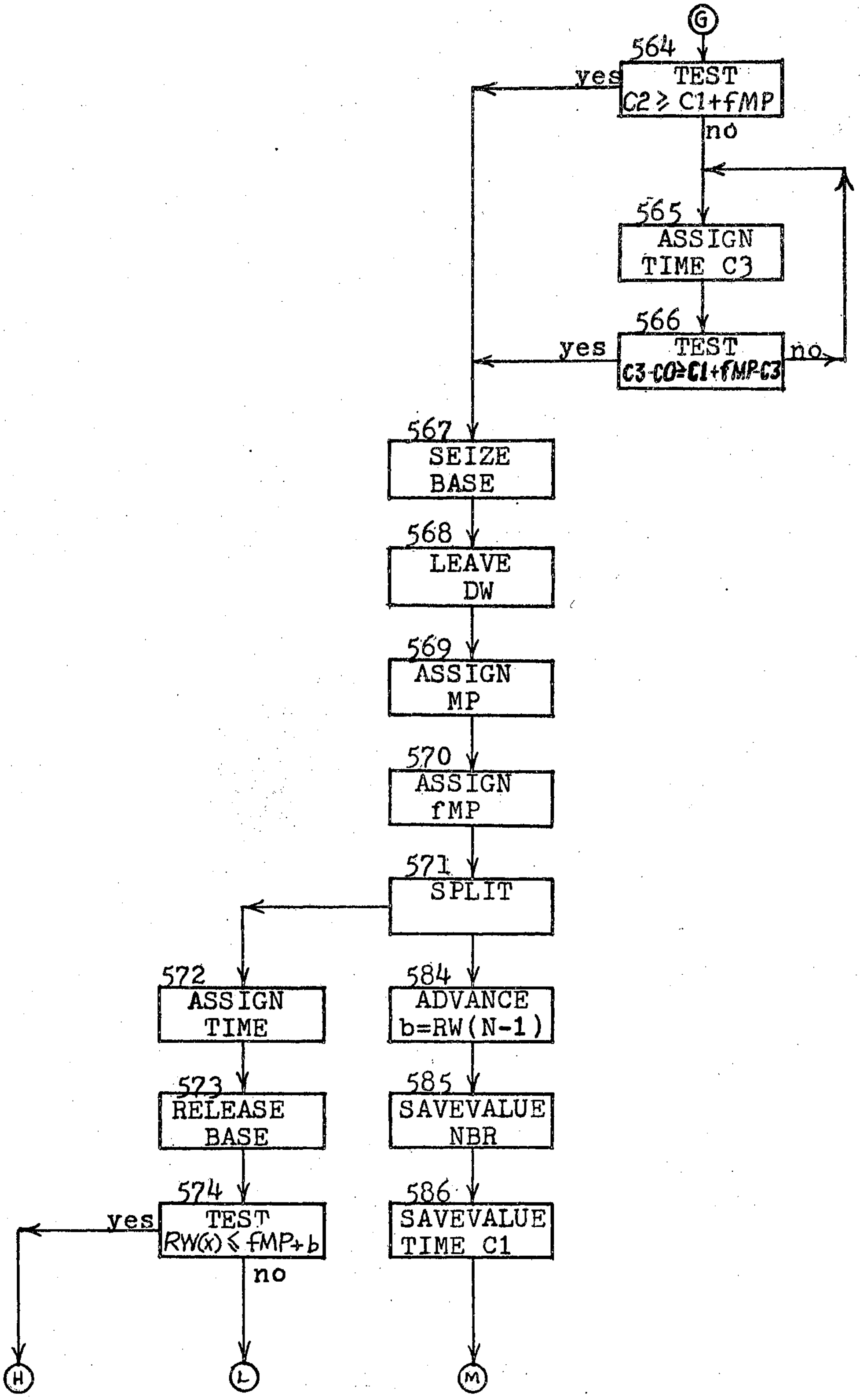

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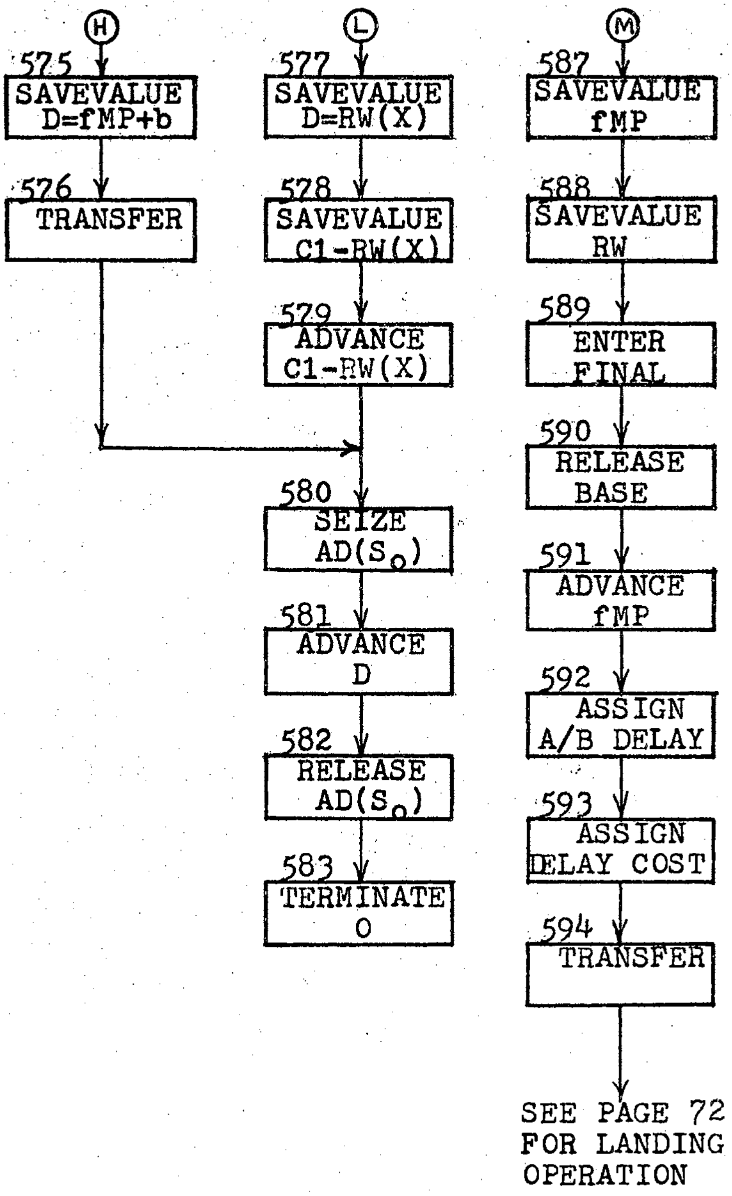

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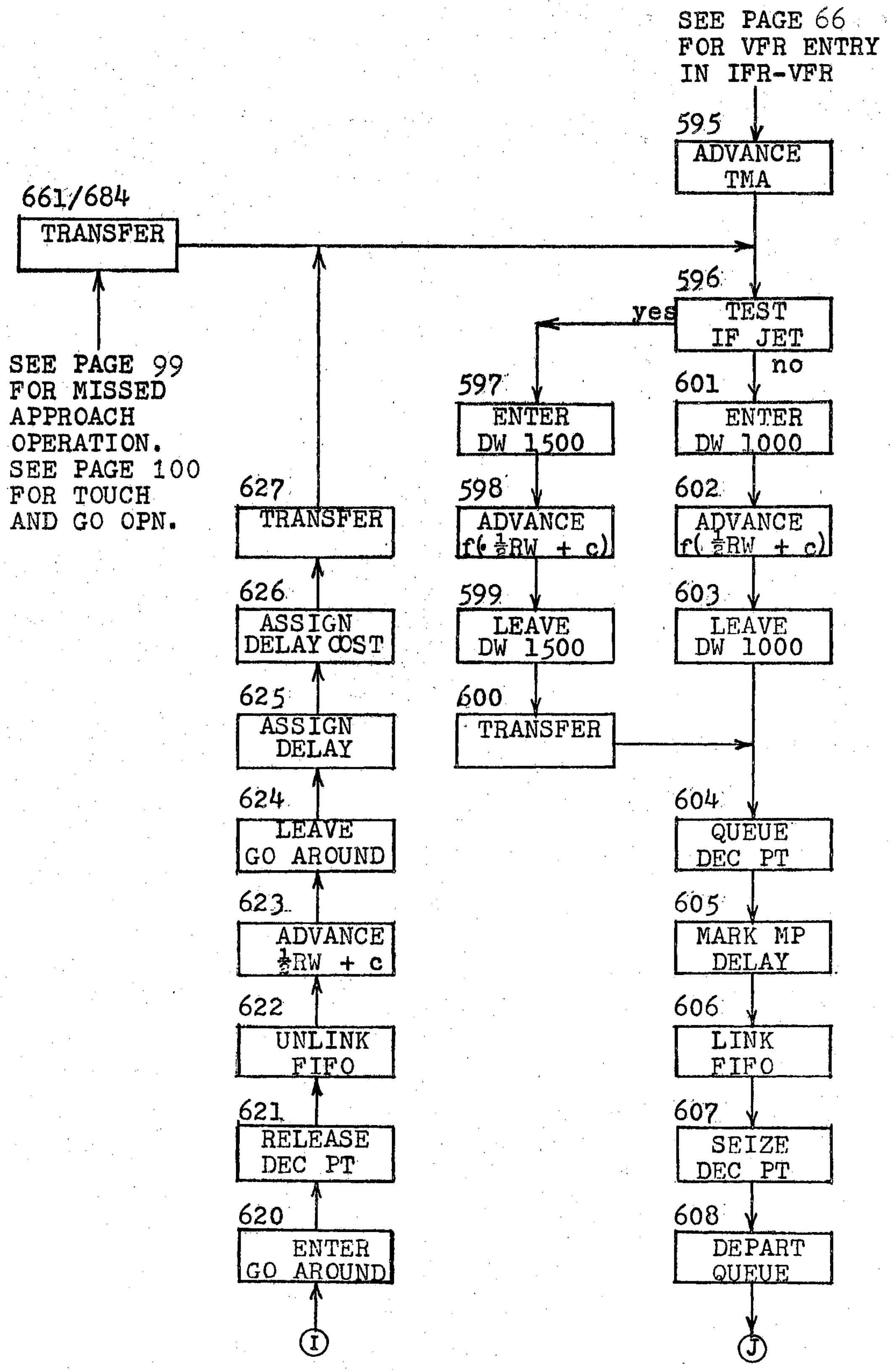

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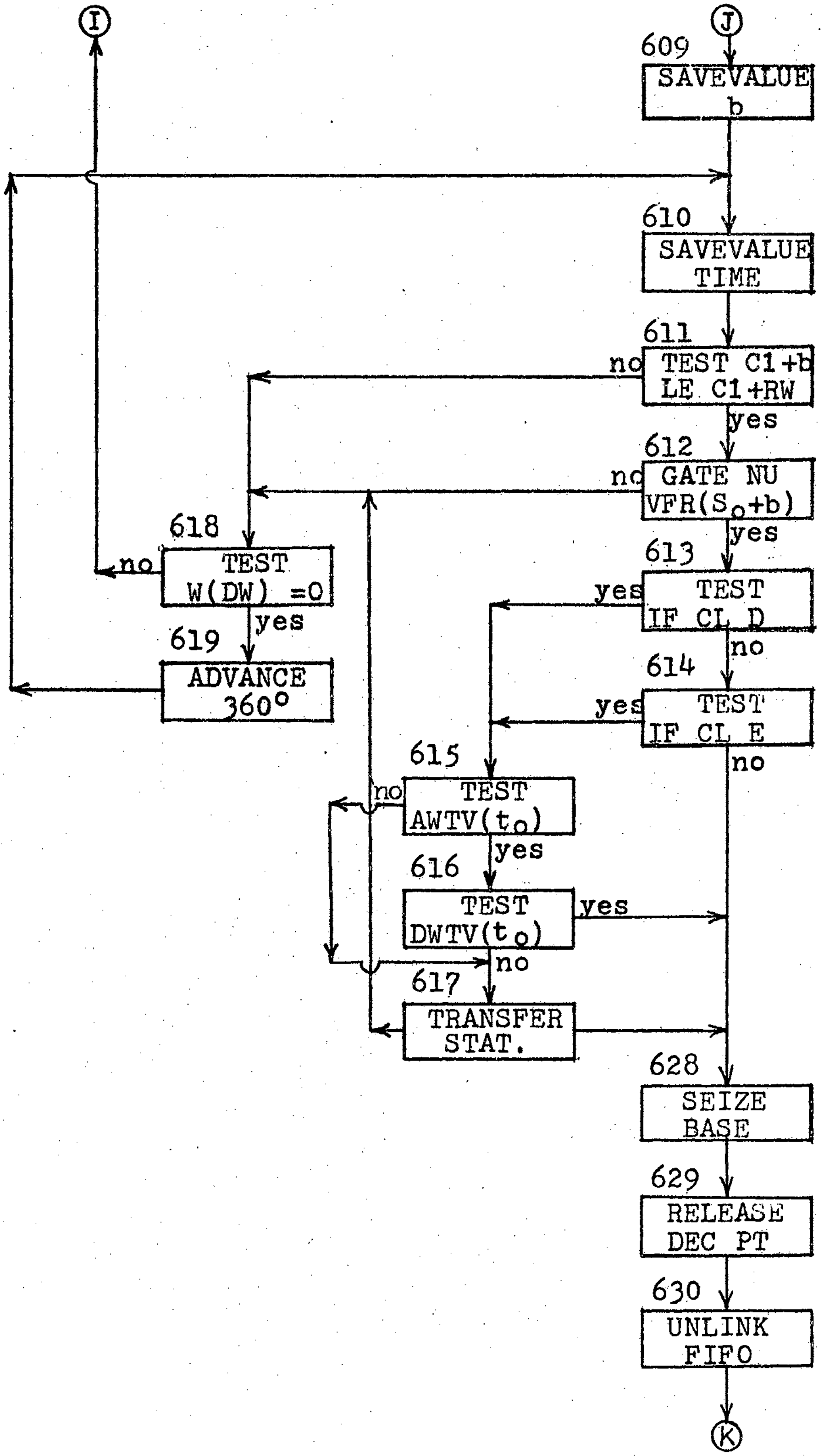

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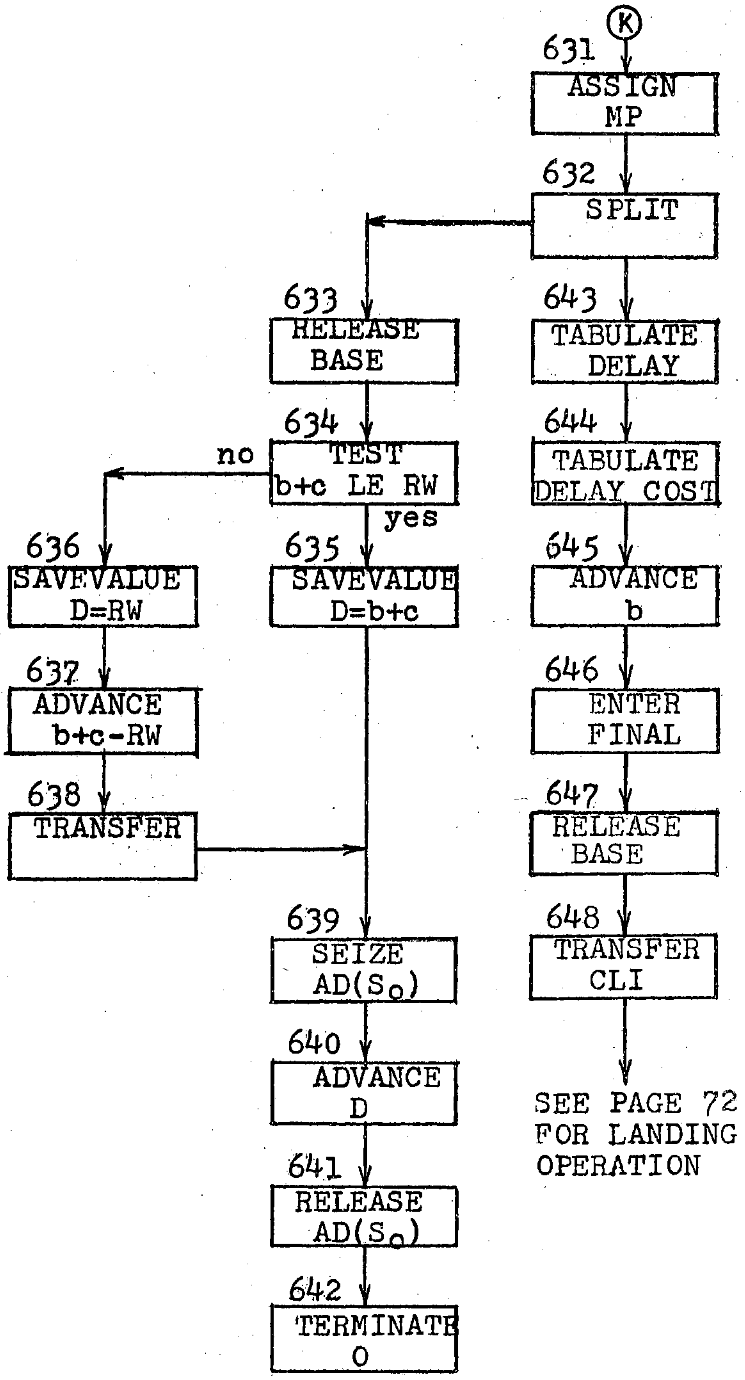

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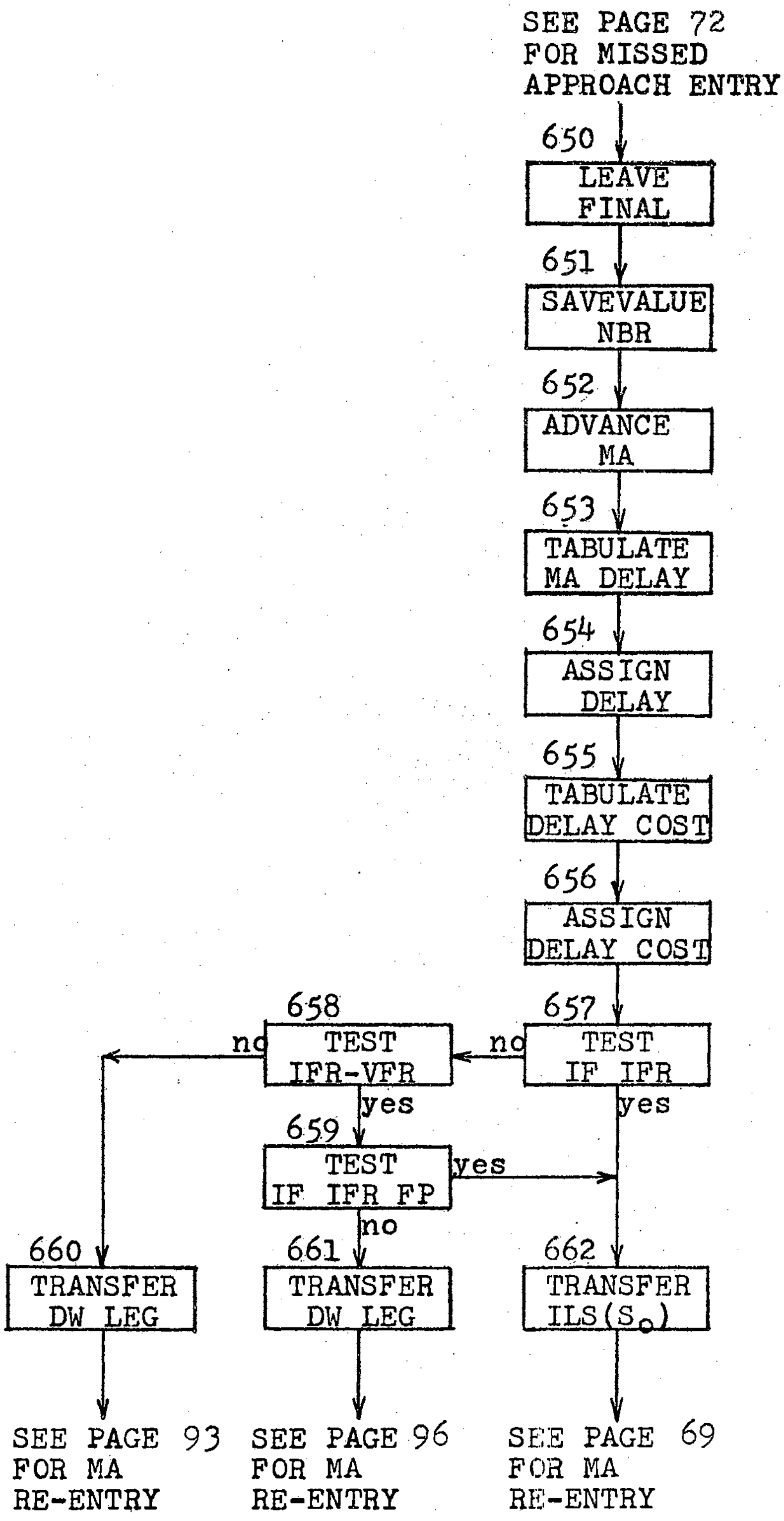

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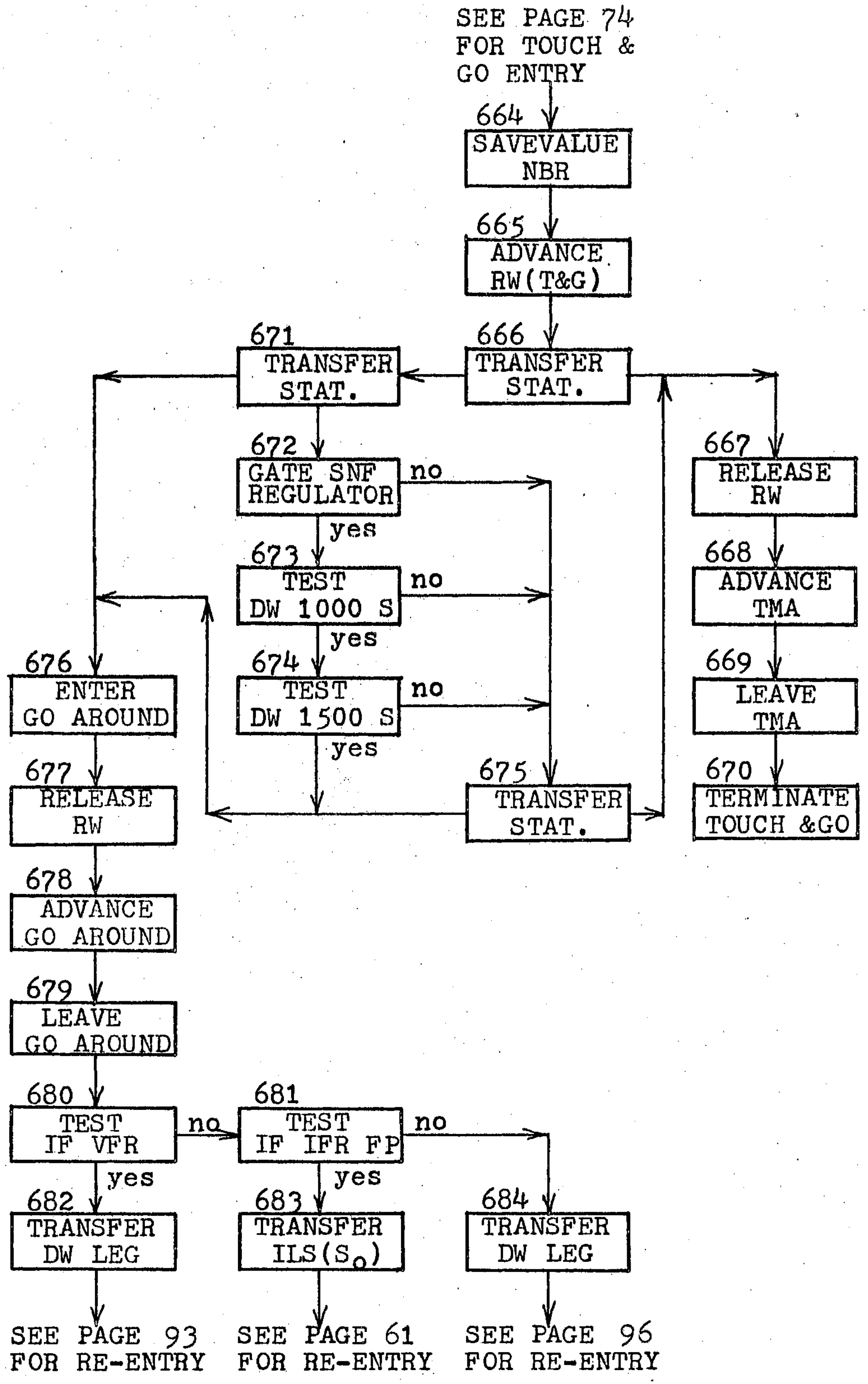

Figure 9. (Continued)

FOOTNOTES

[1] The second should be selected as the basic time unit for an airport system simulation. Tabulated data, however, may be modified by variable statements which in effect, put required values in terms of minutes or hours. An offset interval is specified in multiples of 3600 seconds for each successive generation time period. A limit count is used to deactivate a generate block after a conservatively estimated hour of activity. Since this limit count can not be precisely determined the test procedure must be introduced to determine if the clock time of the activated aircraft is less than or equal to the upper limit of the generation time period. If the activation time is greater than the upper limit of the time period, the transaction is sent to a Terminate block where it is deactivated. Such a deactivation, however, does not deincrement the simulation start count. GPSS IV (IBM 360) greatly improves the rather cumbersome generation procedure described in this thesis by allowing generation in accordance with a function statement. Using such a procedure, two blocks will be capable of defining and activating the same transactions that have taken 97 blocks using GPSS III.

[2] These classes are defined by the Federal Aviation Agency in their Airport Capacity handbooks. Following is a selected listing of types of aircraft in each class: Class A (Boeing 707 and 720, Convair 880 and 990, D. H. Comet, Douglas DC-8); Class B (BAC III, Boeing 727, 737, DC-9, Douglas DC-6, DC-7, Lockheed Constellation); Class C (Aero Commanders, Douglas DC-3, Lockheed Learstar, North American T-39); Class D (Beech Bonanza, Cessna Skynight, D. H. Dove, Piper Apache) and Class E (Aeronca Champion, Beech Musketeer, Cessna 140, 150, 170, 180, 210, D. H. Beaver). These classes are not directly comparable to Terminal Instrument Procedures (TERPS) approach categories which define aircraft according to approach speeds and aircraft weights. (Source: Federal Aviation Agency, <u>Airport Capacity Criteria Used in Preparing the National Airport Plan</u>, (1966), Appendix 2, p. 2)

[3] Possibly a more effective method of introducing the weather factor would be to establish a probability function reflecting a particular airport's expected weather conditions for a twenty-four hour period. Thus the logic switch (32) would change over the twenty-four hour time period in

accordance with the probability function for that period.

[4] In this model the initial approach fix and the holding fix are the same facility. The holding fix may be at any point between the Terminal Area boundary and the ILS outer marker but transfer of aircraft control between the ARTC and Approach Control is usually preferred in a holding area located at the Terminal Area boundary. There may be more than one hold area in a particular airport system, in which case, a decision process would be required to assign the aircraft to the appropriate hold area.

[5] Evaluation of the status of this savevalue may serve as an indication of the need for more holding facilities. If the number of diverts are large, it is likely that a second holding area will be needed. If the number is small, it might be best to add another holding level in the present stack. Since each decision will have an effect on delay and cost of delay, a cost/benefit analysis should be undertaken with respect to the cost of installing and maintaining the added facilities and/or personnel for such expansions of the airport system.

[6] Air Traffic Control procedures in the Terminal Area assume that aircraft are served on a first-come, first-served basis except that landing aircraft have priority over departure aircraft at the runway. Most analysis of the airport system has been based on this criteria. However, virtually every major airport has informally expanded the priority system in order to serve air traffic more efficiently. These informal rules usually give scheduled aircraft priority over unscheduled aircraft; jet over reciprocating engine aircraft; IFR aircraft over VFR aircraft; large or fast aircraft over small or slow aircraft; etc. One researcher, Gerold Pestalozzi, has analyzed priority rules for runway use and found that priorities have little effect on the average arrival delay for the entire aircraft population (though average delay cost can be appreciably influenced) on the capacity rate of the airport. (See: Gerold Pestalozzi, "Priority Rules for Runway Use", *Operations Research*, Vol. 12 (1964), pps. 941-949.) However, some researchers have misinterpreted Pestalozzi"s conclusions and have failed to recognize the considerable influence that priority policy can have on the over-all performance of the airport system. Specifically, there is much less cost, inconvenience and hazard involved in delaying Class E aircraft than there is in delaying a Class A aircraft. Consequently, it seems appropriate to have priority criteria as that mentioned above. However, the analyst will want to study this problem carefully before introducing priorities into his simulation model. It should also be noted that the priority block (92) could have been located anywhere after block 40, however, its present location represents the point in the simulation where it is first needed.

[7] As defined by Simpson, the regulator accepts random arrivals from en route control, or sequences aircraft from the holding stack. In IFR weather, it provides correct spacing intervals between each pair of aircraft in a landing sequence by controlling the path and speed of all aircraft between the holding areas and the ILS outer marker. In this model the capacity of the regulator is arbitrarily defined as three; however, this value is dependent on the terminal area configuration and the approach control policies in effect at a particular airport. (See: Robert W. Simpson, "Analytical Methods of Research into Terminal Area Air Traffic Operations", Journal of Aircraft, II, (May-June, 1965), p. 186.) As will be noted later, the landing aircraft must delay sufficiently in the regulator to insure not only ILS outer marker separation ($S_o = 3$ NM) but also threshold separation (by FAA regulation, $t_o = 2$ minutes; however, in practice the 3 NM separation is maintained throughout the final approach sequence) as once an aircraft enters the ILS it can not alter its speed or path.

[8] There are several other approach procedures. Most are derivations of the two shown in Figure 5 and usually result from multiple stack operations. Another basic approach procedure is one frequently called a "Back ILS". In such a case the landing aircraft flies downwind in the vicinity of the ILS, makes a 180 degree turn and enters the final approach path at the ILS outer marker. This may be a time saving maneuver for aircraft arriving downwind from the airport but it greatly reduces the capacity of a heavily used airport in that the ILS is pre-empted by the landing aircraft on its downwind leg and procedure turn as well as its final approach. This author does not believe this type of approach procedure and its derivatives (such as the overhead approach used by military jet aircraft) have practical application in high traffic density terminal areas.

[9] This value could be tabulated directly by the Tabulate block referring to M1 or the transit time. However, the aircraft will likely incur delay at several points in the airport system and it is desirable to be able to reference the specific delays incurred by each aircraft. (Reference to a table will only provide the statistical mean of the current accumulation of data.) In subsequent accumulations of delay and cost data a Mark MP block is used to note the commencement of delay and an Assign-MP block is used to collect the subsequent amount of delay.

[10] The Link block is used here for two purposes: (1) to save computer running time and (2) to isolate each aircraft during the landing decision process. Specifically, savevalues will be used in the landing decision process and it is essential that the data placed in a savevalue by a landing aircraft not be changed by a trailing aircraft until the

first aircraft has completed its decision process. Another important use of the Link block (which identifies a user chain) is in the structuring of an independent chain of events. This use is not illustrated in this thesis; however, it is a valuable tool in analyzing many complex systems. The symbol FIFO (first-in, first-out) indicates that the first transaction to enter (link) the user chain will be the first transaction to leave (unlink) the user chain.

[11] It is necessary to be able to compute the block departure times for both the aircraft under current consideration and the preceding arrival aircraft. This is done for the aircraft currently attempting to enter the ILS by placing its flight time for the 3 NM separation S_o (107), the final approach path m (108), the minimum stabilization distance c (109) in parameters and the current time Cl (110) in a savevalue. The preceding aircraft on final places its number, commitment-to-land time and minimum stabilization flight time in appropriate savevalues (148-150). The trailing aircraft refers to these savevalues in determining whether runway separations can be achieved. Specifically, the trailing aircraft determines (113) whether its arrival time at the point 3 NM from the runway $\underline{Cl+m - S_o}$ (111) is equal to or greater than the runway threshold time of the preceding arrival $\underline{Cl + c}$ (109/110). When this condition is met, the aircraft may proceed on the assumption that the minimum distance separation S_o will be maintained at the runway. The same procedure is followed for determining (114) the minimum time separation (t_o = 2 minutes under current IFR procedures) at the runway. Specifically, delay is incurred until $\underline{Cl+m - t_o}$ (112) for the trailing aircraft is equal to or greater than $\underline{Cl + c}$ (109/110) for the preceding aircraft.

[12] The wing tip vortice problem is extremely serious to light aircraft (both fixed wing and rotary) following heavy aircraft. The turbulence problem is being investigated by the FAA but at present there are no effective means of determining the necessary separation requirements. Two minutes separation is generally recommended but severe turbulence has been known to last as long as ten minutes. The FAA recommends several procedures as to where a light aircraft should touch down or lift off with respect to where a preceding heavy aircraft touched down or lifted off but these procedures are complicated by shifts in wind, etc. It will be necessary for the analyst to study this problem much further; however, when there is little or no mix of aircraft weight classes, there is little problem with wing tip vortices. The programming of this test follows the procedure described in footnote 12 above.

[13] If the airport has approach control, a departure aircraft desiring to take off in front of an instrument approach must be able to time its take-off so that it will be

clear of the runway before the aircraft on final has reached a point four miles from the runway. Thus the approaching aircraft flies the ILS distance minus four miles or $\underline{m - D(S_o)}$ (131) at which time it activates a facility representing the time required to fly the last four miles to the runway (132-135). The departure aircraft will check to see if this facility is in use and if it is, it will not be allowed to take off.

[14] If the airport has no approach control, a departure aircraft desiring to take off in front of an instrument approach must be able to time its take-off so that it will clear the runway before the aircraft on final is at a point three minutes from the runway. Therefore, the approaching aircraft flies the ILS distance minus the three minutes or $\underline{m - D(t_o)}$ (136) at which time it activates a facility representing the time to fly the last three minutes to the runway (137-140). A departure can not be authorized while this facility is in use.

[15] In mixed IFR-VFR operations it is a normal policy to direct the VFR to a holding point near the end of the runway (assumed herein to be a distance equal to the minimum stabilization distance c) and to be released for final approach such that the VFR aircraft can reach the commitment-to-land point (which for light aircraft is essentially the end of the runway) without infringing upon the inter-arrival separation requirements of the trailing instrument approach. If b represents the time required by the VFR aircraft to fly its base leg then the interarrival separation to be met by the VFR aircraft at the time of release from its holding point is $S_o + b$, where $S_o = 3$ NM. Thus the aircraft entering the ILS flies the distance $\underline{m - (S_o+b)}$ (142) at which time it activates a facility (143-146) representing a landing clearance refusal for a VFR aircraft. /The IFR aircraft determines the value b from a savevalue (609)./

[16] Another use of a savevalue is as a storage for a value which has been selected randomly from a distribution and is used in computing a future block departure time. In such cases it is necessary to retain the selected value for the subsequent advance block operation rather than randomly select another value for the advance block. If the savevalue is susceptible to being changed by a trailing aircraft before the saved value can be used, a parameter (assign block) should be used rather than a savevalue. The reader will recall from footnote 10 that the link/unlink (user chain) block was used to protect values in a savevalue by allowing only one aircraft at a time in the decision submodel.

[17] The number of diversions is accumulated in a savevalue (164) and may be used in the investigation of the ef-

fectiveness of a particular air traffic control scheme. Currently, a missed approach rate of about one percent is considered acceptable. A higher rate is usually associated with relaxed separation criteria (excepting the basic rule of only one aircraft on the runway at any given time) while a lower rate is associated with a very stringent separation criteria.

[18] There is no formal logic that can be established for such cases, thus, the planner or analyst will have to estimate such probabilities from past experience. A more comprehensive use of this procedure would be to establish a probability that the runway is closed by an accident, loss of lights or navaid equipment, or closed because of a momentary weather condition.

[19] The analyst will need to ascertain the policies of the particular controllers involved as there are no formal rules for such operations. It might seem odd that an aircraft requesting a touch-and-go is requested to land if the airport is too busy (thus adding to the ground congestion); however, the controller is most concerned with the number of aircraft in the air. Consequently, by having this aircraft land he has reduced the number of aircraft to be controlled in the air.

[20] Note that the exit assignment should reflect landing speed and distance requirements, as well as exit location and design. A problem that has generated much comment is that of the effectiveness of high speed exits. Such exits may be designed for speeds of up to 60 m.p.h.; however, experience has shown that this type of exit is seldom used at over 15 m.p.h. When designed and located properly the high speed exit can be a great benefit in reducing runway occupancy time; however, due to the rapid changes in aircraft technology, many existing high speed exits have become obsolete due to design or location. A further problem relates to the stress limits that can be applied to landing gear of heavy aircraft. Thus the high speed exit is truly a problem in systems analysis.

[21] There are two queues for this intersection and indirect specification is used in denoting which queue is being referred to. Specifically, the Depart block does not specify the argument directly; rather, it specifies an address where the argument (i.e., the specific queue in this case) is located (a parameter number). It should be noted that even though the aircraft already on the high speed taxiway have a higher priority than those leaving an exit, their priority is not pre-emptive; thus, once an aircraft enters the intersection from an exit, all other aircraft, regardless of priority, must wait for it to vacate the intersection before attempting to enter themselves. Depending on the amount of traffic and the complexity of the taxiway

system, taxiway delay can be a very significant figure.

[22] This procedure assumes that there is a by-pass area where reciprocating aircraft can run up without delaying jet aircraft behind them. Many departure exits either do not have this capability or have an inadequate capacity.

[23] It should be noted that the advance times (such as 335) reflect the optimum time to move the required distance. Any time in transit above the advance time is considered delay.

[24] This value is referenced by VFR arrival aircraft in establishing the required separation minimum that the departure must be able to maintain if a take-off is to be authorized.

[25] This model assumes a common departure route of less than 13 NM; consequently, the initial separation required of successive departures is 3 NM until courses diverge. The preceding departure executes a savevalue reflecting the time it will reach a point 3 NM beyond the end of the common path (403). The time required for the trailing aircraft to take off and fly the length of the common path is computed (Cl + RW + d) and is tested (354) to determine if it is equal to or greater than the time in the above mentioned savevalue (403). If this condition is met the required interdeparture separation can be maintained.

[26] Many airport controllers will allow a departue aircraft to move onto the runway if the required separation with respect to an arrival is met. However, in such cases the aircraft must take out its interdeparture separation requirements at the end of the runway. Some interdeparture separation requirements may be as much as three minutes; thus, the runway is pre-empted for use by subsequent arrivals for an unnecessarily long period of time. This model assumes that all departure delay will be taken out on the exit, none on the runway. Angled departure exits greatly facilitate the time required for take off under such a policy.

[27] As used here the Link block (which specifies a user chain) acts primarily to reduce computer running time by restricting the decision process for terminal service to only the first aircraft in the queue.

[28] There are many ways of structuring the terminal model. This airport model has four open ramp gate positions and it is assumed that each has the same service capabilities as the others. A more complex terminal will have gate positions for specific types of aircraft and for individual airlines. It should be realized that the concepts expressed thus far are equally applicable to the terminal building and

the ground access system.

[29] There are innumerable ways of interpreting the configuration and activities of a parking ramp. The model shown here is intended only to show how basic aircraft operations might be described. No service function is described for local aircraft because it is assumed that these aircraft will be parked and then serviced whenever convenient (i.e., the transient aircraft have a pre-emptive priority over service facilities).

[30] It should be noted that the trombone is most effective when only aircraft of similar speeds are in the system. Under such conditions the trombone is probably the most efficient approach system available. However, when there is a wide mixture of aircraft classes, or when instrument approaches are also being performed the trombone can cause very large interarrival gaps which, in turn, cause excessive delay and low airport capacity. Thus two models are assumed in this thesis: TheVFR trombone, which is used in VFR only conditions (i.e., no IFR operations); and the VFR approach pattern in mixed IFR-VFR traffic. This latter model does not employ the trombone feature and will be described later.

CHAPTER IV

APPLICATION OF THE SIMULATION PROCEDURE TO PROBLEMS IN AIRPORT PLANNING

As defined in Chapter I the airport problem consists basically of : (1) an immediate need to optimize the use of existing airports to meet present air transportation demand and (2) a long range need to develop an entirely new airport system that will be responsive to the dynamic growth expected of air transportation demand and technology.

This chapter discusses how the simulation procedure described in Chapter III can be applied to both aspects of the airport problem.[1]

Model Construction

While the degree of detail required of a specific simulation model can vary considerably depending on the complexity of the system being investigated, the amount of time and funds that can be devoted to the project, the quantity and quality of input data available, the programming capability of the analyst and the capability of the computer equipment available, it is essential that the model be sensitive to the status of critical elements in the system being simulated.[2] Specifically, if influence is applied to a particular element of a system, the model must be capable of sensing and recording the secondary effects that will be distributed, to one degree or another, to all other elements of the system. It is therefore the analyst's task to define and costruct a model which will determine the location, character and significance of these systems effects. To do this the analyst usually must establish a set of rules for problem analysis and model construction. A typical set of such rules are as follows:[3]

I. Determine the Structure of the Airport System
    1. Prepare a detailed description of all processes or situations effecting the airport system.
    2. List the factors which are independent or otherwise not under the control of airport or aviation industry management.
    3. List the factors which can be regulated or controlled by airport or aviation industry management directly.
    4. List the dependent factors and their suspected relationship with the independent factors.

II. Construct Simulation Models
    1. Construct flow diagrams which describe the inter-relationships suspected from initial investigation.
    2. Decide what numerical and other information will be necessary to test the validity of the models under consideration.

3. Collect statistically adequate samples of information (or organize experiments or procedures for collecting the information). If little real information is available, at least determine the range of values the various factors can take and make assumptions (that can be agreed upon by all parties concerned) about the characteristics of such factors.
4. Using this data and the flow diagrams, write computer programs for the simulation models. Test for the model that most accurately represents the situation being simulated. Test the behavior of this model over the entire range of feasible values.
5. If the model does not give the required accuracy (based on statistical tests), modify the model and repeat the previous stages until a suitable model has been constructed.
6. Determine the sensitivity of the model's behavior to small or large changes in the values of various factors.
7. Lastly, decide what information, in what detail, is required about each factor to give the analyst a picture of the situation being studied to a degree of accuracy sufficient for his purpose.

Once the model has been validated (by statistical tests), it can be employed to predict the likely effects of any further modification of the system or situation within the framework of the model. The information resulting from such modifications will in most cases indicate, at least on a relative basis, the course of action to be taken to achieve any given objective.

There are innumerable ways in which the simulation procedure may be applied to airport problems; however, two basic applications will be stressed here: (1) development of a comprehensive data base for Cost/Benefit and/or Cost/Effectiveness analysis and (2) to determine the "systems effect" of any change in the airport system (either in physical design or operation).

Cost/Benefit and Cost/Effectiveness Analysis

Finding a solution to an airport problem is not the only major task a planner faces. Once this solution has been determined there is the problem of convincing airport or aviation industry management that the solution is sufficiently valid to justify the expenditure of funds (which invariably amount to sums of considerable magnitude). One of the most significant uses of the simulation procedure described in Chapter III is that it allows the analyst to detect exactly where, when and in what amount, costs or benefits are incurred in an airport system. This data, tabulated in terms of operational delay to aircraft (or other units of traffic), delay cost, total operational cost and facility utilization, can be presented in any desired amount of detail to airport or aviation industry management. Thus, mangement has a scientifically rather than intuitively developed base of operational and economic data with which to make effective decisions concerning the design and operation of an airport system.

In applying the simulation procedure for the purpose of economic analysis, the airport system analyst faces three basic problem situations:

I. The airport is in existence; however, it is not efficiently handling its traffic demand. The analyst must determine the most economic means of increasing the operational capability of the airport to meet current demand. After constructing a model that describes the current situation, the analyst begins to modify the design and/or operation of the system as a means of evaluating alternative solutions. /‾However, because of the time required to implement major physical modifications, he will need to emphasize modification of operating procedures. Areas to be investigated include air traffic control procedures (such as noise abatement procedures), airline scheduling practices and use of major hub airports by general aviation aircraft. In addition, the analyst should investigate the possible benefits that might result from small scale construction or equipment installation.

(Shortening an ILS, adding a second holding area, or adding a second departure route can often provide more benefit to the airport system than the addition of a much more expensive physical improvement.)7

II. The airport is in existence and operating relatively efficiently; however, there is a need to prepare a master plan which will allow the airport to continue to function effectively in the face of rapidly growing demand. The analyst must determine the most economical method of staging construction to ensure that the airport is able to meet future demand. After constructing a model representing the current system and its operation, the analyst begins to increase demand in accordance with traffic forecasts. When the airport system reaches capacity, design and operational modifications are introduced and investigated as a means of increasing capacity. The analyst thus determines (1) when a modification is needed and (2) what type. Such evaluations must be made with respect to some standard of efficiency (acceptable delay, facility utilization, etc.).[4]

III. The airport is in the early stages of planning. The planner must determine the most economical design capable of meeting the forecast traffic demand. The analyst constructs several possible models and tests them with respect to the forecast traffic demand. (The analyst must be extremely careful in establishing assumptions for such models, as they are very difficult to validate.)

Determining the Systems Effects

A major problem faced in all planning is that of failing to consider the importance of secondary effects that result from applying a change to a particular element of a system. Systems analysis is essentially directed toward correcting this situation. Thus a major application of the simulation procedure is that of allowing the analyst to determine the location and criticalness of any secondary effect that might arise from the application of a particular solution he is considering.

In such cases the analyst constructs a model of the initial system and then modifies it according to the proposed change. The simulation model is then tested to determine not only the direct effects of the modification, but also the criticalness of secondary effects (that are experienced to one degree or another by every other element of the system) incurred elsewhere in the system. An analysis is then made to insure that the direct benefits of the proposal under consideration are justified with respect to any liabilities resulting from secondary effects experienced elsewhere in the system.

FOOTNOTES

[1] The Terminal Area Air Traffic Control System is emphasized as the critical element in the airport system. While other elements of the total airport system (such as the terminal facility) present major problems, they do not directly effect the movement of air traffic and, at present, do not experience delay, cost and safety problems of the same magnitude as those experienced by aircraft. However, if airport development continues to lag aircraft and air traffic control development, it is very possible for such elements as the terminal to become the critical factors in the airport system.

[2] It should be noted that the procedure described in Chapter III is subject to several programming limitations. For example, the IBM 7040 has a core storage capacity of about 32,000 bytes. The IBM 360, however, has a minimum core capacity of 64,000 bytes and can be modified to allow capacities of 128,000, 256,000 and upward. The number of blocks in a particular program is also limited. For example, the IBM 7040 will allow 500 blocks while the IBM 360 will allow between 120 and 1,000 depending on the configuration of the computer. The number of a particular type of block is also limited. For example, the IBM 7040 will allow 200 Facility blocks while the IBM 360 will allow between 35 and 300 depending on the computer configuration. Most of these computers have an automatic reallocation feature which allows the programmer to "trade off" block types. Specifically, if the programmer needs ten more Facility blocks he can reduce the number of Queue blocks by that number (provided he does not need the ten Queue blocks). Thus the programmer and analyst must work together to determine how to best allocate computer resources in the construction of a simulation model. More importantly, the analyst must be able to use "trade-off" analysis effectively in determining what elements of the system can sacrifice programming detail without reducing the analytical capability of the over-all model.

[3] R. R. P. Jackson and P. A. Longton, Operational Research and Aviation Management, _Journal of the Royal Aeronautical Society_, LXIX (August, 1950), p. 547. It should be noted that the referenced material applied only to mathematical models; however, with only slight modification these rules become equally applicable to computer simula-

tion models. This relationship again illustrates the analytical power of the systems approach.

[4] Leonard H. Quick, "Megalopolis Airport Requirements", (paper presented before the Third Conference of the American Institute of Aeronautics and Astronautics, 1967), p. 3: "Experience in the planning of facilities has indicated it is better to err on the high side rather than the low. The high cost of trying to catch up with demand usually exceeds the cost of reasonable over-capacity. This is especially true in airport development because accelerating land appreciation makes incremented expansion extremely costly." In addition Mr. Quick comments: "We should not expect an airport to have an infinite life. Aircraft technology is one of the most progressive fields of science. It is not unreasonable to expect that major airports must be remodeled, redesigned, or even phased-out, as the aircraft they were designed to support are obsoleted by advancing technology." Ibid., p. 5. In addition to Mr. Quick's observations it should be noted that there are increasing numbers of situations where inadequate airports are being modified in a manner which creates additional operating costs greater than the cost of abandoning the airport and developing an adequate airport elsewhere.

CHAPTER V

SUMMARY

It is becoming increasingly apparent that a systems approach must be introduced in airport planning and development. The systems approach requires that a particular problem be viewed in the widest perspective possible according to analytical capability. It is only when total systems effects can be adequately investigated that truly effective planning can be accomplished. To plan in this manner requires a greater analytical capability than is available from manual resources. It is necessary to introduce the computer as a tool when attempting to analyze complex systems. Utilizing the techniques of computer simulation, the airport planner can for the first time comprehensively investigate the airport in terms of its systems nature.

Proposals for Continued Research

The procedure described in Chapter III, inspite of its length and complexity, is in its infancy with respect to its potential as a tool for comprehensive systems analysis. There is an urgent need to advance this technology to the point that it is caple of investigating: (1) the total airport system (to include at least the Terminal Air Traffic

Control System, the terminal system, and the ground traffic systems); (2) the total transportation system (as it reflects the total trip experience of the air traveler or item of air freight); (3) the hierarchal character of a system of airports (to determine the location and criticalness of systems effects among several airports); and (4) the airport as a major land use and socio-economic element within an urban or regional environmental system. The concepts underlying the simulation procedure presented in this thesis are equally applicable to each of these problems.

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APPENDIX A

TERMINAL AREA AIR TRAFFIC CONTROL PROCEDURE

The terminal area is a controlled airspace surrounding an airport and is used by aircraft to progress from one point to another (airways); to approach or depart from a runway (final approach and initial departure courses); and to perform delaying tactics (holding in stacks or path stretching). The terminal area is the most critical element of the entire Air Traffic Control System because of the high concentration of aircraft arriving and departing in many directions, circling in holding stacks, positioning for final approach, landing and taking off. All of these operations require a somewhat more stringent system of control than that needed along the airways. The terminal area is modified by airspace reservations assigned to each operational runway. These reservations are rectangular sections whose size is determined by the operational requirements of the aircraft using the particular runway. Airports serving class A, B, or C aircraft (DC-3 type or heavier) reserve an airspace 15 miles in the approach direction, 10 miles in the departure direction and 5 miles on either side of the extended runway centerline. For airports having parallel approaches, the width is 10 miles plus the distance between the runways. Airports serving class D or E aircraft (twin engine or lighter) reserve 10 miles in the approach direction, 5 miles in the departure direction and 4 miles on either side of the extended runway centerline. The above reservations are established primarily for IFR operations; however, some airports have no IFR capability, in which case they establish circular airspace reservations with a radius of 3 miles if the airport is used only by class D and E aircraft and 5 miles if used by class C or heavier aircraft.

Holding Procedures

Since air carriers invariably operate under IFR procedures at airports with IFR capability regardless of the weather conditions (light fog, smog and exhaust from jet departures frequently create IFR conditions even though the weather indicates VFR conditions) this discussion will emphasize the procedures used in controlling IFR operations. (VFR operations are discussed in greater detail in Chapter III.)

Inbound aircraft are directed from the enroute airways to a holding fix. These holding fixes are determined by radio beacons located at specified geographical locations around the perimeter of the terminal area. As aircraft normally land and take off into the wind the holding fix is located downwind from the "runway-in-use". Aircraft directed into the holding pattern fly an oval or "race track" pattern consisting of 1 or 2 minute turns (the initial turn being performed over the holding fix) and 1, 1.5 or 2 minute straight legs. Apart from tracking the holding leg up to the fix point, no guidance is available to pilots flying the pattern. Because of wind effects and possible navigation error, buffer areas surround the prescribed holding pattern. This combined area is designated the holding area and constitutes an airspace reservation. A vertical separation of 1,000 feet is maintained by aircraft in the holding stack. The process of controlling the descent of aircraft within a holding stack is known as "laddering" since each pressure level or 1,000 foot step of the ladder must be vacated before the next aircraft is cleared to descend. Normally the first aircraft to arrive at a holding fix has been directed by ARTC to the lowest level of the stack (if there are no aircraft in the holding or approach patterns, an arrival aircraft is directed to pass through the holding area without delay), with following aircraft directed to successively higher levels. The first aircraft to arrive is normally the first aircraft cleared for landing approach. From the holding pattern aircraft are either directed by radar to a position from which the final approach can be made or instructed to carry out the appropriate approach procedure without radar control.

Approach Control Service

Most major airports have established an Approach Control Service which has the responsibility for Air Traffic

Control Services for IFR flights engaged in arrival or departure operations. Control of arrival aircraft is "handed off" from ARTC to Approach Control at some pre-designated point or time, usually when the aircraft arrives at the holding fix. The Approach Control unit is provided with flight information and issues clearances for approach and departure operations. Approach Control ladders aircraft in the holding stacks, regulates their exits so as to form an efficient and safe landing sequence and spaces aircraft before the ILS outer marker by means of path stretching. The time at which each aircraft is to leave the holding pattern for an approach is specified by Approach Control sufficiently in advance to permit the pilot to arrange his flight path so as to leave the holding point at the specified time. Clearance for descent to final approach level must also be given by Approach Control. Each succeeding aircraft is cleared to leave the holding pattern and to descend to approach level at a specified time when Approach Control has determined that the required landing interval has been established by the preceding aircraft. (Under current IFR procedures a minimum radar separation of 3 miles must be developed in the approach area prior to the ILS outer marker and a minimum arrival interval of 2 minutes must be maintained at the runway threshold.) Approach Control regulates aircraft from one or more holding stacks into a "funnel" formed to channel aircraft onto a common path required for ILS guidance during final approach. In this area the pilot is following instructions from the ground controller and guiding his aircraft according to various radar vectors without any direct knowledge of the desired path or the position of the preceding aircraft.

The ILS is an adoption of the VOR systems for landing purposes. It consists of two radio transmitters located on the airport, with one beam called the localizer, and the other called the glide slope. The localizer indicates to the pilot whether he is left or right of the correct alignment for approach and the glide slope indicates the correct angle of descent to the runway. In IFR conditions the minimum common path for an ILS approach is from the ILS outer marker to the runway threshold (usually about 5 miles in length); however, aircraft are normally funneled onto the ILS localizer a few miles previous to the outer marker. The glide path can be thought of as a line drawn from an imaginary gate in space to the threshold of the runway. Aircraft enter the gate one at a time in order of arrival. The actual length of the path depends on the location of navigation equipment and the aerodynamic stability of aircraft using the approach. If an airport has no Approach Control Service, aircraft operating under IFR conditions continue to be controlled by ARTC through the necessary holding and sequencing procedures prior to entry onto the ILS. Upon entry onto the ILS, an aircraft's control is handed off from ARTC to the airport Control Tower.

If a pilot desires to execute a Ground Controlled

Approach (GCA) the Approach Control informs him when to change over to the radar unit, the frequency to be used and the procedure to be carried out. GCA is performed in conjunction with a Precision Approach Radar (PAR) system in which a split-screen radar scope gives the controller a picture of the descending aircraft both in plan and in section (elevation). Thus the controller is able to determine whether the aircraft is on the glide path and whether it has the correct alignment. Instructions from the controller to the pilot are given by voice communications; thus no navigation equipment (such as the ILS) is necessary. However, commercial airline pilots use ILS almost exclusively on the grounds that PAR places too much reliance on the ground controller and does not provide any direct information to the pilot. (These pilots, however, often request that their approach be monitored by PAR.)

The FAA is currently developing a three-dimensional radar system which will enable controllers to receive a single image representation of an aircraft's azimuth, range and height in relation to all other aircraft in the Terminal Area. This system, designated the Alpha-Numeric System, offers promise of increased positive control in air traffic control operations.

The U. S. Air Force and the U. S. Navy have both recently flight-tested fully automated landing systems. The Air Force program involved landing C-130 cargo aircraft while the Navy test involved carrier landings by jet fightter-bomber aircraft. It can be expected that a capability for fully automated approach and landing operations at civil airports will exist in the very near future.

Normally the control of an aircraft is handed off by Approach Control to the airport Tower Control at the ILS. In the event of a missed approach, the aircraft flies a prescribed recovery procedure, which takes it back into the radar vectoring funnel leading to the ILS and returns it to the jurisdiction of Approach Control.

Airport Traffic Control

The airport traffic control tower supervises, directs and monitors the traffic on and above the airport and in the final approach and initial departure paths. Tower Control is provided with flight information and issues clearances for all operations involving aircraft movement on the airport. Tower Control also has the authority to suspend all VFR operations on and in the vicinity of the airport.

The primary rule involving runway use is that two aircraft cannot occupy a runway simultaneously. Thus a landing aircraft is permitted to cross the runway threshold on its final approach only when the preceding arrival has turned off the runway and any departing aircraft has either cleared the end of the runway or has started to turn away from the runway. Aircraft under GCA are handed over to Tower Control upon landing.

The Airport

A defined area of land including buildings, installations and equipment intended for use in the arrival, departure or surface movement of air traffic is called an airport. The movement area consists of runways, runway exits, taxiways and service aprons. Exits of various approach angles (usually 30 to 90 degrees) facilitate the removal of a landing aircraft from the runway. For a 90 degree exit, a landing aircraft must slow virtually to a stop before turning; whereas a 30 degree exit, theoretically, allows a landing aircraft to exit at speeds up to 60 m.p.h. (In practice, however, pilots seldom use these exits at speeds over 15 m.p.h.) Aircraft may be guided from the runway along taxiways to the apron via voice communication from the Control Tower, by a system of taxiway lights, by a "follow me" truck or by the pilot's own knowledge and initiative. Some of the larger airports have an apron control service which provides taxiway and apron traffic control for both aircraft and autos.

The apron permits the loading and unloading of passengers, mail and cargo as well as servicing and storage of aircraft without interferring with airport traffic movement. For departing aircraft, holding aprons (run-up areas) are provided at or near the ends of the departure runway. These aprons allow departing aircraft to make final checks before requesting take-off clearance. These aprons also allow for the storage of a number of aircraft waiting for departure clearance.

Departure Control

An aircraft desiring to depart the airport initiates a request to taxi from the parking ramp, and from the holding apron requests a clearance to move onto the active runway for departure. Departure Control has received the depature's flight plan and issues a clearance which specifies the direction of take-off, turn after take-off, track to be made good before proceeding on desired heading, level to maintain before continuing to climb to assigned cruising level, and the time, point or rate at which level changes will be made. (Normally, the clearance is passed to Tower Control which transmits it to the aircraft and instructs the aircraft to switch to Departure Control after take-off). However, the take-off clearance is issued only after the pilot has tested engines, received weather information, time check, altimeter setting and ARTC clearance.

A departure can be released in front of an arrival aircraft making an instrument approach at any time prior to the arrival aircraft starting its procedure turn leading to final approach or whenever the take-off can be executed 1 to 3 minutes prior to the arrival crossing the threshold. (1 minute for VFR conditions, 3 minutes for IFR conditions). A departure is usually not released for take-off until the preceding departure has crossed the end of the runway and all preceding arrivals are clear of the runway.

Initial departure route separation must be a minimum radar separation of 5 NM and 2 minutes between departures following the same track or 1 minute if the tracks diverge immediately after take-off. A 5 minute minimum separation is required at the time cruising levels are crossed, if a departing aircraft will be flown through the level of a preceding departure and both aircraft propose to follow the same track. Upon entering an airway, control of a departure is handed off from Departure Control to ARTC.

APPENDIX B

GENERAL PURPOSE SYSTEMS SIMULATION

The IBM General Purpose Simulation System (GPSS) is a computer program for conducting evaluations of systems, methods, processes and designs. The following material has been extracted from the IBM Application Manual H20-0186-1 (1966):

Computer Simulation Defined

> Because of the complex nature of modern business systems, data processing aids are increasingly required to assist the intuition and judgment of management in the evaluation of new methods, concepts, or designs. The practice of experimenting directly on a business and implementing a system before it is fully understood inevitably causes disruptions of normal operations, hasty last-minute corrections, and often personnel or customer resentment. To avoid costly mistakes, the consequences of change must be anticipated before actually implementing a program, and all alternatives should be thoroughly explored.
>
> Computer simulation is a technique that provides an effective means of testing and evaluating a proposed system under various conditions in a laboratory environment. The system's behavior is modeled by a computer program, which reacts to various operating conditions in a manner quantitatively similar to the system itself. Several hours cr weeks, or sometimes even years, of simulated activity can be examined on a computer in a matter of minutes. Results help to gain insights, test hypotheses, demonstrate or verify new ideas, establish feasibility, compare alternatives, design systems, or train personnel.

It is appropriate to any discussion on simulation to add a few words of both caution and encouragement. Computer simulation, like any simulation, is not a precise analog of an actual system. What is studied is the behavior of a representation of an actual system. Therefore, careful judgment must still be exercised by the user, both in setting up a good model and in interpreting the results from the simulation.

On the other hand, computer simulation frequently permits measurements which would be impossible to obtain in any other way, and allows the study of environmental situations of a scope far beyond the practicability of experimenting with an actual system. Such abilities as these immeasurably enhance the value of computer simulation in its role as an engineering and management-science tool.

General Purpose Simulation System

Computer simulation is recognized as a valuable tool for business managers, systems engineers, and functional specialists alike. Writing simulation programs from scratch, however, is a difficult, time-consuming task, requiring complex and extensive programming. To be most useful, a simulation must be carried out quickly and be adaptable to change as the work proceeds. The General Purpose Simulation System greatly simplifies this task, and offers substantial additional values to the user. It is easy to apply, and no machine programming is required, nor is typical computer programming experience or training necessary. It is applicable to the study of a wide variety of situations ranging from bank teller queues, supermarket service, and job shop organizations to vehicular flow patterns, message-switching systems, etc. The program features a simple flowchart language for describing the problem or system to be simulated. When this description is transferred to punched cards and presented as input to the computer, the program automatically carries out the simulation of the system.

Operating Highlights

To understand the operation and range of application of GPSS, one can begin with the familiar process of systems analysis.

The first step in the analysis of any particular system is to isolate the system's elements and formulate the logical rules governing their interaction. The resulting description is known as a model of the system. The model is limited to those aspects of the system which are of interest or appear to be pertinent to the analysis.

The progress of sytems studies is greatly enhanced by the introduction of a concise systems language. To illustrate this, we consider two apparently unrelated systems.

In the first, ships arrive at a small port with a known arrival pattern. While in port, the ships unload some of their cargo, taking a certain amount of time, and then proceed on their voyage. There is only one pier, and if a ship arrives while another is unloading, it must wait. If several ships are waiting, the one that arrived first will be unloaded first. Of interest here is the total amount of time that a ship will spend in port, including the time spent waiting for the pier to become available.

In the second system, requests from retail outlets arrive at a warehouse where there is only one clerk to fill them. If requests occur too close together a backlog builds up. These requests are processed in the order in which they arrive. The question here is: How long does it take a request to clear the warehouse?

Considering these two systems, several similarities can be seen. Both are characterized by units of "traffic" (ships, requests) arriving at a facility (pier, warehouse) requiring service. The facility can handle only one unit of traffic at a time, and if this facility is busy when new arrivals occur, these units must wait and form a queue or waiting line. Thus, three general elements are common to both systems: units of traffic, a facility, and a queue.

Also, the underlying logic of the two systems is identical. This may be demonstrated by means of a flowchart displaying system action. Figure 10 presents the simple harbor system described above, laid out in flowchart format. This shows the interaction of the pier and arriving ships. Figure 11 presents the simple warehouse system, showing interaction between the clerk and arriving requests. By replacing the terminology of harbors

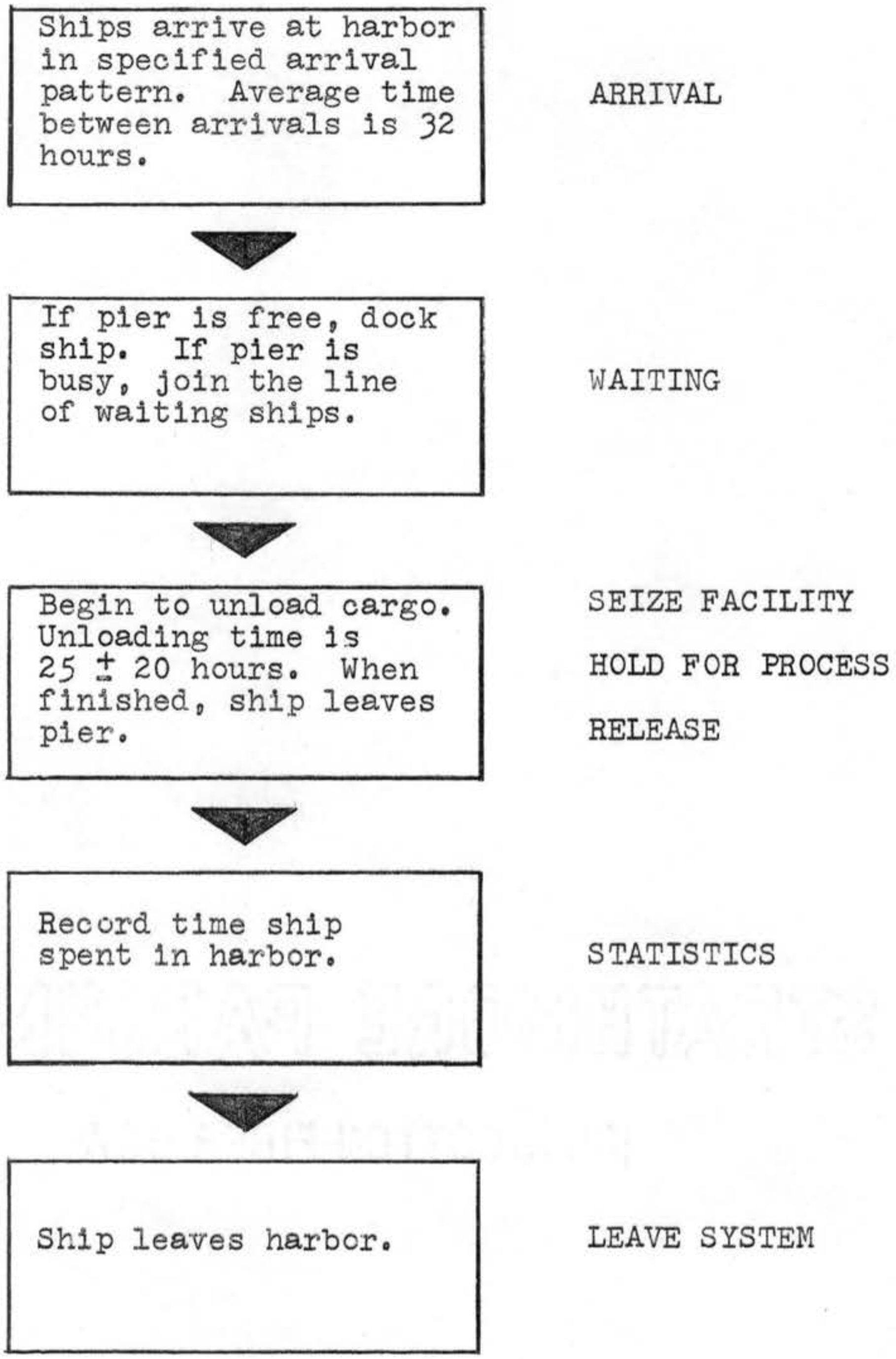


Figure 10. General Flow Chart for a Simple Harbor System

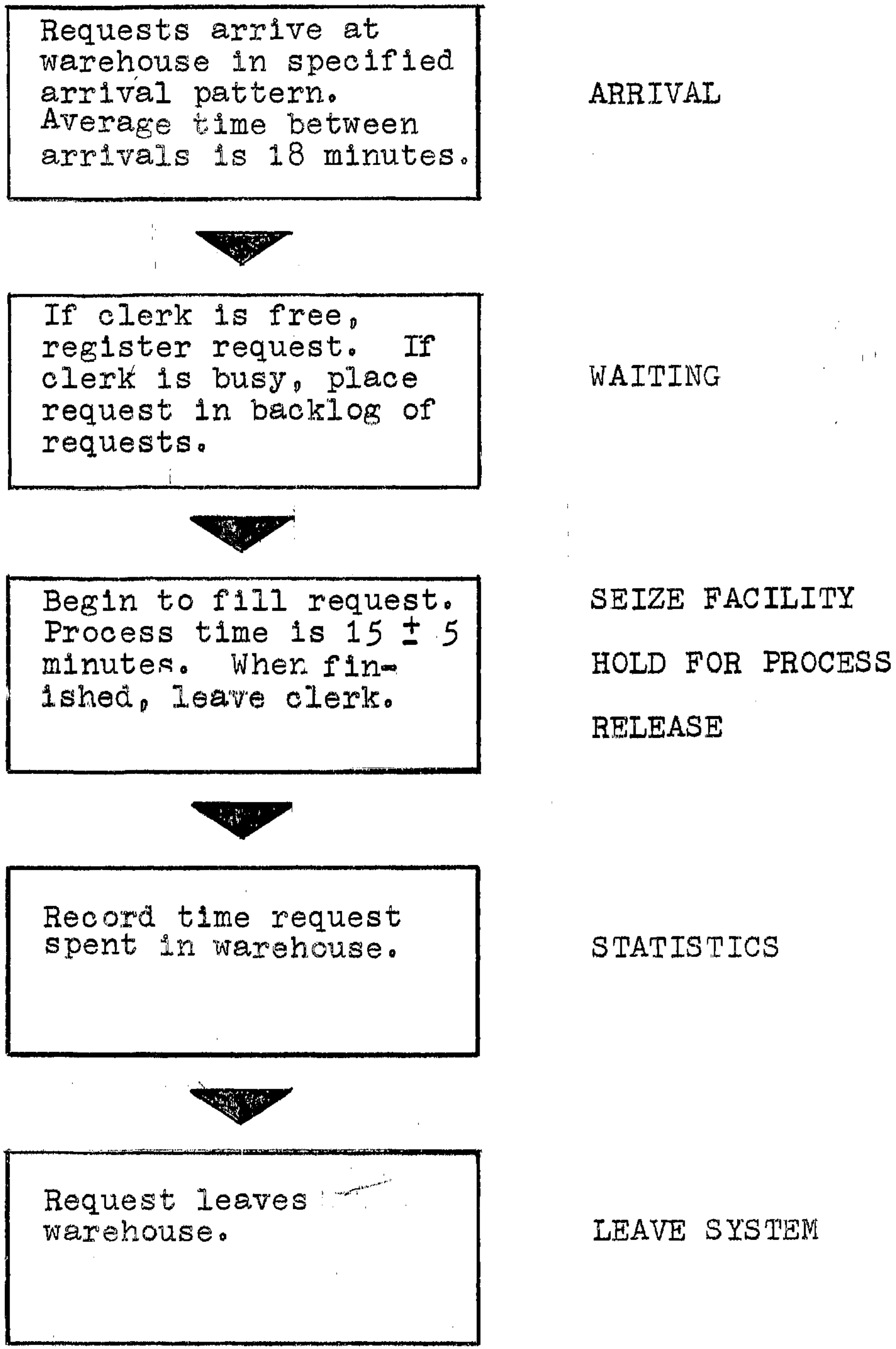


Figure 11. General Flow Chart for a Simple Warehouse System

and ships with warehouses and requests (also changing specific time values), it is readily seen that Figure 10 also describes the logical operation of Figure 11 and vice versa.

After examining several such diverse and much more complex system models, it becomes evident that many generalizations concerning them can be made. The system elements of each, which appear so different on the surface, may be logically replaced by a small set of abstract elements called "entities". Likewise, the logical rules may be reduced to a common set of simple operations. Thus, a systems language can be developed containing abstract entities and operations involving these entities. By identifying these entities and operations with specific elements and logical rules in a particular system, a model of that system may be constructed in the general language.

The GPSS program provides such a general systems language. It is built around a set of simple entities, divided into four classes: dynamic, equipment, statistical, and operational.

The dynamic entities in GPSS are called "transactions". These represent the units of traffic, such as ships or requests in the previous examples. They are "created" and "destroyed" as required during the simulation run, and can be thought of as moving through the system causing actions to occur. Associated with each transaction are a number of parameters, which can be assigned values by the user to represent characteristics of the transaction. For example, a transaction representing a ship might carry the amount of cargo it is to unload in a parameter. This number could then be used in the simulator logic to determine how long the unloading operation would take.

Entities of the second class represent elements of system equipment that are acted upon by transactions. These include facilities, stores, and logic switches. A facility can handle only one transaction at a time, and could represent the simple pier or warehouse in the examples given. It represents a potential bottleneck. A store can handle several transactions concurrently, and could be used to represent a parking lot or a typing pool. A logic switch is a two-state indicator which can be set by one transaction to modify the flow of other transactions. It could model a traffic light or the "next window" sign of a bank teller.

In order to measure system behavior, two types of statistical entities are defined: queues and tables. Each queue maintains a list of transactions delayed at one or more points in the system, and keeps a record of the average number of transactions delayed and the length of these delays. A table may be used to collect any sort of frequency distribution desired. These two entities provide a major portion of GPSS output.

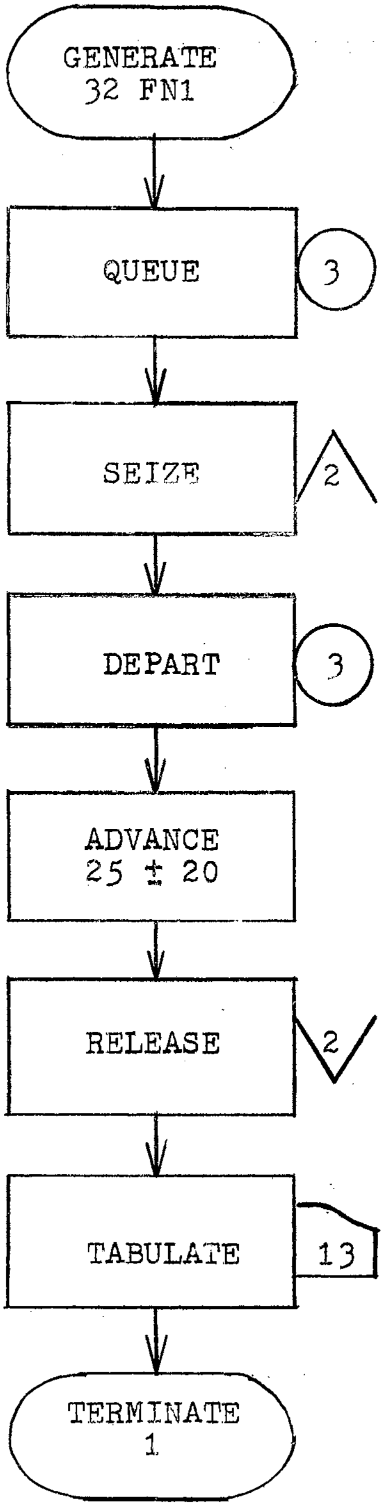
The operational entities, called "blocks", constitute the fourth and final class. Like the blocks of a diagram, they provide the logic of a system, instructing the tranactions where to go and what to do next. These blocks, in conjunction with the other three classes of entities identified above, constitute the language of GPSS.

As an example of this language, the simple harbor system outlined in Figure 10 is diagrammed, using conventional GPSS symbols as shown in Figure 12. Each box represents a specific GPSS block, with its name and usually the number of a referenced entity.

To provide input for the simulation, control and definition cards are prepared from a flowchart of the system. This constitutes the model in GPSS language. Once the system model is loaded, the GPSS program generates and moves transactions from block to block according to timing information and logical rules incorporated in the blocks themselves. Each movement is designated to occur at some particular point in time. The program automatically maintains a record of these times, and executes the movements in their correct time sequence. Where actions cannot be performed at the originally scheduled time - for example, when a required facility is already in use - processing temporarily ceases for that transaction. The program automatically maintains a status of the condition causing the delay, and as soon as it changes, the transaction is activated again.

This sequence of events is controlled by a simulation clock that records the current time reached in the modeled system. Values shown by this clock are referred to as clock times. The unit of simulator clock time representing a unit of system time is designated by the user. For example, in Figure 12 the unit of clock time equals one hour.

Many more system complexities can be modeled than



Generate transactions (ships) at an average rate of one every 32 time units (hours). Arrival pattern specified by a function (FN1).

Queue up transaction (ship) in queue 3, if facility 2 (pier) is busy.

Seize facility 2 (pier) if it is free or, when it becomes free, make it busy.

Depart from queue 3, since transaction (ship) is no longer waiting for facility 2 (pier).

Advance time while this transaction is delayed (ship loaded) for 25 ± 20 time units (hours).

Release facility 2 (pier), making it free.

Tabulate in Table 13 the total time spent by transaction (time ship was in harbor).

Terminate transaction (ship leaves harbor).

Figure 12. GPSS Flow Chart for the Simple Harbor System

are illustrated by the example. Priorities can be assigned to selected transactions, and complex logical decisions may be made throughout a simulation. Probability distributions of input variables may be introduced into the model, and provision is made to gather statistical output with ease.

Output from the program provides information on:

- o The amount of transaction traffic flowing through the complete system and/or any of its parts
- o The average time for transactions to pass through the complete system or between selected points, and the distribution probability of this passage time
- o The degree to which each item of equipment in the system is loaded, together with the distribution of storage occupancy
- o The maximum and average lengths of queues occurring at various points, as well as their distribution

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