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KNOWLEDGE-BASED RUNWAY ASSIGNMENT FOR ARRIVAL AIRCRAFT IN THE TERMINAL AREA

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Abstract

A knowledge-based system for scheduling arrival traffic in the terminal area, referred to as the Final Approach Spacing Tool (FAST), has been implemented and operationally tested at the Dallas/Fort Worth Terminal Radar Approach Control (TRACON) facility. Two types of controller advisories are generated by FAST: sequence number and runway assignment. The knowledge base for runway assignment employs a set of hierarchical rules and decision logic that evaluates both performance and workload criteria. This formulation is based on over 2,000 hours of controller-in-the-loop, real-time simulations. In the field tests, controllers had the option to accept or reject the FAST-generated runway assignments. Results indicate strong adherence to the advisories and increased capacity, with no significant impact on controller workload.

Introduction

Runway assignment of arrival aircraft is a tactical decision made by controllers. Strategic re-assignments, or allocations, assist in balancing controller workload and reducing delay, but are difficult for controllers because of the high workload already associated with the traffic load. As terminal area controllers become consumed with the task of separation, strategic runway allocation becomes neglected. During high workload periods, controllers simply assign runways to fill available landing slots when aircraft are well within TRACON airspace. This process of tactical adjustments to the arrival schedule requires coordination between controllers and ultimately leads to higher workload and increased delay. Any system which attempts to alleviate this problem must consider controller workload. This report describes such a system; the knowledge-based runway allocation algorithm for an air traffic automation tool called the Final Approach Spacing Tool (FAST).[1,2,3] FAST is the terminal area component of the Center/TRACON Automation System (CTAS).[4]

The runway allocation algorithm in FAST attempts to achieve runway load balancing and increased capacity without increasing controller workload. Previous research focused on optimization of delay reduction. Optimization of a cost function requires that all relevant inputs be quantified. Therefore, if controller workload is considered important, it must be quantified. Brinton attempted to represent workload as a series of terms in a cost function, however, his implicit enumeration algorithm did not adequately address this issue and was found unacceptable by controllers.[5] The runway allocation function provided by FAST employs a knowledge base obtained through thousands of hours of simulation with expert controllers. This knowledge base incorporates controller preferences and workload into the runway allocation problem. By doing this, FAST emulates the decision patterns of expert controllers, while using accurate calculations of aircraft performance to reduce delay in a manner acceptable to controllers.

This paper begins by defining the motives and potential benefits of runway allocation. The runway assignment algorithm employed by FAST is described, as well as the rules used to create the knowledge base. Results of operational testing of FAST at the Dallas/Fort Worth TRACON facility are briefly discussed, followed by some concluding remarks.

Runway Allocation Motives and Benefits

As aircraft enter TRACON airspace, they are typically assigned by the controller to the closest runway to the arrival feeder gate. This default assignment defines an initial arrival plan. Adjustments are made to the arrival plan, as the aircraft approach the runway, by assigning aircraft to alternate runways. This process is known as runway allocation, and is the primary means of balancing arrivals to each runway and controller workload. Runway allocation decisions made by controllers in

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today's system are tactical adjustments to the arrival schedule prompted by near-term concerns. As traffic volume and workload increase, controllers have less time to evaluate potential runway allocations. Strategic runway allocation is lost at high controller workload levels. This void in strategic decision making could be filled by a decision support system. To develop such a system, it is necessary to comprehend the factors that necessitate runway allocation.

Runway Allocation Motives

Several factors can lead a controller to assign a new runway to an aircraft. Factors such as airline preference, shortest flight time, and controller preference dominate during periods of low demand; while workload reduction drives decision patterns during high demand periods.

Airline preferences are usually determined by parking gate location, and perceived taxi time to the gate. During rush periods, controllers are less likely to accommodate airline preferences, as this increases their workload due to increased coordination between controllers and more issuance of clearances if no slot is available on the desired runway.

Controller preferences stem from a variety of issues. For example, even at low workload, comfort is gained through knowing an aircraft has more vectoring options available if a problem arises: an aircraft may have more available airspace for maneuvering if assigned to one runway over another, with no significant impact on delay. During low workload periods, controllers have time to evaluate the arrival plan and make runway allocations which result in reduced delay. This is accomplished through coordination with other controllers and the ability to recognize available landing slots on alternate runways. However, because the default runway is usually the closest runway, this type of allocation is rare during low arrival rates.

As the number of aircraft handled by a controller increases, the number of required commands increases, as does the time required to issue these commands. It is essential for a controller to limit workload to a level at which the system is controllable and safe. The complexity of merging streams and insuring separation increases and at some level becomes the only task the controller can effectively perform. This means less time will be available to evaluate strategic runway allocations. Unfortunately, the controller with the highest workload has the least time to accurately evaluate the evolving problem. Decisions which affect workload are often made too late to be of significant benefit. The fundamental problems with strategic decision making by terminal area controllers are twofold: 1) the controllers having the necessary information to evaluate potentially beneficial decisions, have no time to do so and 2) evaluation of the problem itself becomes more complex and time consuming as the potential benefits increase.

Potential Benefits Of Automated Runway Selection

Decision support tools for runway assignment could fill the void left in strategic decision making during high workload periods. A number of benefits could be realized from automated runway assignment: workload balancing, increased throughput, and delay reduction.

By providing decision support for runway assignment, the terminal area controller has more time to perform the task of separating aircraft. With proper runway selection, less coordination between controllers would be necessary to accommodate late runway changes. However, the primary workload benefit is workload balancing. Extremely high workload for a single controller in the TRACON complicates the entire system, thus requiring increased coordination between controllers. Balancing the number of aircraft landing on each runway insures workload is evenly distributed among the final controllers. Balancing workload between controllers reduces both the workload of the busiest controller, and the coordination between controllers. Furthermore, runway balancing may reduce surface congestion, taxi time and departure delay.

Runway balancing is a methodology that attempts to provide each runway with adequate demand. The actual runway threshold throughput can only reach the airport capacity if demand meets or exceeds capacity on each arrival runway. It is not possible to consistently meet minimum separation on each runway if sufficient demand does not exist for each runway. Effective runway balancing insures sufficient demand exists for each runway at high arrival rates. Unbalanced runways can result in the demand for a given runway greatly exceeding the capacity, while another runway's capacity exceeds demand. Excess demand for a runway leads to flight time delay to land all the aircraft assigned to that runway. Runway balancing attempts to match a runway's demand with its capacity, thus eliminating delay due to capacity shortfall. Some additional flight time may be required to land on an alternate runway, but this additional time is often less than the required delay to land on the default runway. Furthermore, TRACON delay reduction through maximum utilization of all runways, could lead to increased TRACON acceptance rate from Center airspace. Increased acceptance rate translates into reduced delays in Center airspace during metering.

Requirements For An Operational System

For a runway assignment decision support system to be operationally acceptable in today's ATC environment, four requirements are realized: acceptable workload, schedule stability, trustability, and cost reduction.

The primary concern of controllers is safety. Safety can be linked to workload and thus any system that makes a controller feel on the edge of safe operation, due to high workload, is unacceptable. Controller workload is difficult to quantify; instead, controller acceptability is generally evaluated through surveys such as NASA-Ames' Controller Acceptance Rating Scale (CARS).[6]

The schedule advised by the decision support system must not appear variable to the controller. While minor instabilities may be acceptable in advising the sequence of aircraft in a "close-call" situation, instabilities in runway advisories are unacceptable. The runway advisories displayed to controllers handling aircraft as they first enter the TRACON can determine when and to whom aircraft are handed off (transfer of control) to next. Instability in runway advisories would lead to an increase in handoffs, controller workload and stress.

Some level of trust in the system must be gained in order to realize the potential benefits of the advised schedule. If a controller takes a "wait and see" attitude on a fully acceptable advisory, the advised solution may eventually become unacceptable. Trust is gained through familiarity with the system, stability, and observed benefits.

Finally, an ATC decision support tool must realize benefits. Benefits are largely achieved through increased throughput at the airport.

FAST Knowledge Based Runway Allocation

The foundation of the FAST runway allocation algorithm lies in the wealth of information provided by accurate 4D trajectories. FAST employs an extensive database of aircraft performance models, continuous radar updates, flightplan information and 3D weather predictions to produce accurate 4D trajectories, estimated times of arrival (ETAs), route deviation possibilities, and advisories to controllers. The inputs used by the FAST Knowledge Based Runway Allocation (KBRA) algorithm will be discussed in this section, followed by an overview of the KBRA algorithm. The rules and criteria used to implement the knowledge base developed for DFW TRACON are included in the Appendices.

KBRA Inputs

There are four inputs to the KBRA algorithm: airport configuration, 4D aircraft trajectories, available degrees of freedom for each aircraft, and the relative sequence of arrival aircraft. Each input is now briefly discussed.

Airport Configuration: An airport configuration is chosen by the traffic manager for each airport in the TRACON. The configuration is determined by wind direction and magnitude, visibility, traffic load, and various other factors such as ongoing runway maintenance. For FAST, the airport configuration defines: runways available for arrivals, default runway assignments, potential runways for each arrival traffic stream, and the runway allocation window for each runway.

Each traffic stream (stream class), consisting of aircraft of common engine type arriving through a given feeder gate, is mapped to a default runway. The default runway is usually the closest available runway to the traffic stream's feeder gate. The nature of an arrival rush may lead to a runway other than the closest being mapped as the default in order to strategically balance default runways for arrivals across all available runways.

In addition to mapping the default runway for each traffic stream, possible alternate runways are defined by the airport configuration. Due to standard operating procedures and workload considerations, not all runways available for arrivals will be defined as potential runways for all traffic streams. This reduces the scope of the runway allocation problem and prohibits allocations which would lead to high controller workload.

The runway allocation window for each runway defines a window in time for which aircraft are eligible for runway allocation by FAST. The times are referenced to the fastest time to the final approach fix of each runway. The allocation window is selected to terminate at a time corresponding to aircraft locations just outside the feeder gates, thereby providing stable runway assignment advisories that can be easily implemented early in the control of each aircraft.

Accurate 4D Trajectories: A trajectory generation engine produces accurate 4D trajectories by integrating point mass equations of motion along a horizontal route with specified altitude/speed constraints. The resultant 4D trajectory is broken into trajectory segments for use by the FAST sequencing and runway allocation algorithms.[7] Reducing each trajectory to a set of trajectory segments is analogous to how a controller approaches the merging aircraft problem. Trajectory segments simplify the problem for a controller because they dictate where a controller can expect an aircraft to be in the near future, and where aircraft need to merge with other aircraft onto the next trajectory segment. Figure 1 illustrates an aircraft and its trajectory broken into four trajectory segments: LONG, DOWNWIND, BASE and FINAL.

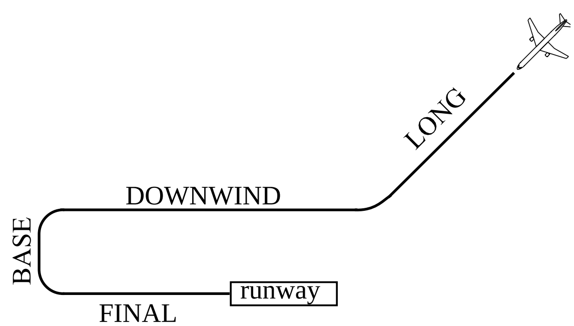

Figure 1. Division of Aircraft Trajectory into Segments

Available Degrees of Freedom: TRACON controllers employ degrees of freedom (DOF) for aircraft to avoid conflicts and merge aircraft streams within their airspace. Typical DOFs for arrivals to the TRACON include speed reductions, base extension and varying intercept angles. Figure 2 shows the base extension DOF.

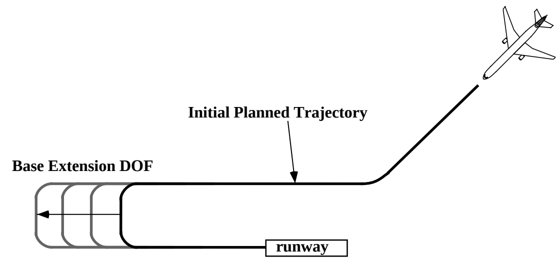

Figure 2. Use of Base Extension Degree of Freedom

The set of all available DOFs are defined for each aircraft based on location, aircraft type and airport configuration. The potential delay effects of each DOF are calculated by producing a set of ETAs corresponding to both full and no employment of each DOF available. Given the relative order between two aircraft determined by the sequencing logic, conflicts are resolved by adding delay to the trajectory of the trailing aircraft through employment of the appropriate DOFs available (as shown in Fig. 3).

Trajectory Segment Ordering for Deconfliction: The deconfliction algorithm requires ordered lists of all aircraft sharing common trajectory segments. That is, if an aircraft is to be checked for conflicts with the aircraft ahead on each trajectory segment, it is necessary to create a sequenced list of aircraft for each trajectory segment in the airspace. These lists of aircraft are referred to as "constraints". The list of aircraft belonging to each constraint is built as each aircraft's trajectory is dissected into trajectory segments. The sequence of the aircraft within each list is determined

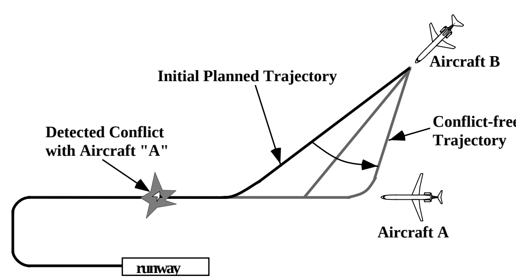

Figure 3. FAST Conflict Detection and Resolution

by the FAST knowledge-based sequencing (KBS) algorithm.[7] The result of the KBS is a sequence of aircraft for each FINAL constraint in the system. However, it is not sufficient to simply employ the sequences obtained from the sequencing for each FINAL trajectory segment in the deconfliction algorithm: some aircraft share segments prior to

FINAL, but land on different runways or even at different airports, as shown in Figure 4 (Aircraft B and C).

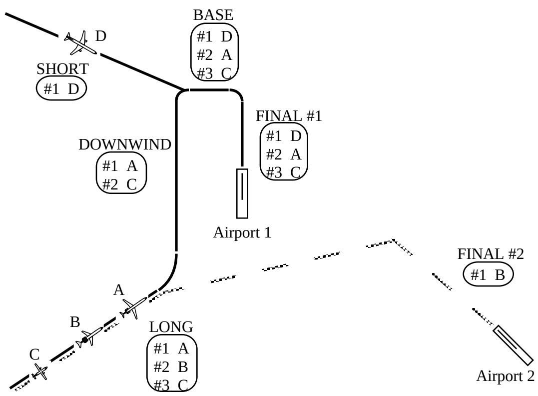

Figure 4. Trajectory Segment Ordering

Also shown in Figure 4, the relative sequence between two aircraft on FINAL trajectory segments is maintained across all segments. All aircraft sharing a given trajectory segment are included in the ordered list for that segment, regardless of which FINAL segment terminates each trajectory. This indicates that Aircraft C will absorb any necessary delay to insure separation with Aircraft B on the LONG segment and Aircraft A on the DOWNWIND, BASE and FINAL#1 segments. An important result of this process is that an aircraft will likely depend on, and therefore be de-conflicted from, different aircraft depending on the order for each trajectory segment.

KBRA Outputs

The output of the knowledge based runway allocation is an advisory to the controllers suggesting a runway for each aircraft. If the controller chooses to accept this advisory, the runway becomes the assigned runway for that aircraft.

KBRA Algorithm

This section describes the KBRA algorithm and its integration into the FAST architecture. First, an overview of how the runway allocation algorithm is integrated into the FAST update cycle will be presented, followed by descriptions of the individual components of the KBRA algorithm.

FAST updates the arrival plan every 6 seconds, operating asynchronously with the TRACON radar, which updates every 4.7 seconds. Within the FAST

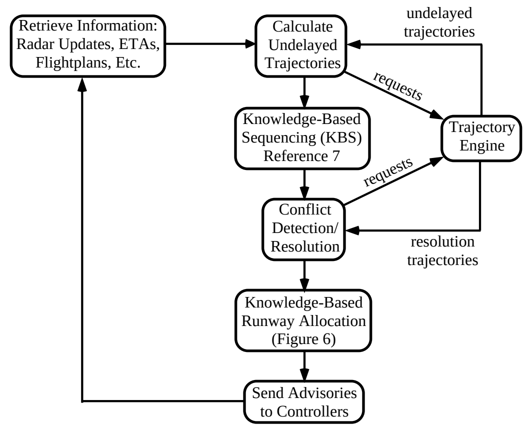

Figure 5. FAST Scheduler Cycle

update cycle, the following is achieved: sequences and STAs are calculated for each aircraft, potential runway allocations are evaluated and resulting sequence and runway advisories are sent to the controllers. As shown in Figure 5, evaluation of potential runway allocations occurs after sequencing and conflict detection/resolution of the arrival plan has occurred. The results of the knowledge-based sequencing and conflict detection/resolution are used in evaluation of runway allocations.

As shown in Figure 6, the runway allocation algorithm is divided into two cycles: the preliminary evaluation of all potential allocations, and the final determination of a single, most promising allocation.

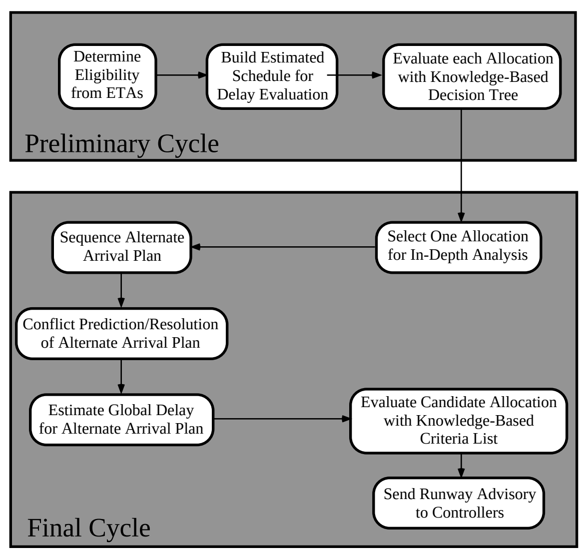

Figure 6. Knowledge Based Runway Allocation Flowchart

Preliminary Cycle

The purpose of the preliminary cycle is to reduce the set of possible tactical runway allocations to a manageable set and to quickly evaluate these allocations. Reduction of the set of all aircraft and potential allocations is first achieved through a test for runway allocation eligibility.

An aircraft's eligibility for runway allocation is largely determined by the airport configuration and its undelayed arrival time or ETA. Specifically the requirements for eligibility are:

1) The aircraft has an available alternate runway. This requires that more than one possible runway be defined in the airport configuration for the aircraft's stream class.

2) The undelayed time-to-fly to the available alternate runway is within the runway allocation window defined by the airport configuration. The allocation window is defined independently for each arrival runway in the configuration.

3) The runway assignment has not been "frozen." A frozen runway assignment indicates that only the controller is allowed to assign a new runway to the aircraft. A frozen runway results when a controller manually assigns a runway to the aircraft, or when the aircraft's time-to-fly to its assigned runway is less than the minimum defined by the runway allocation window.

An aircraft can be eligible for allocation to more than one runway. For this reason, the algorithm employs a runway-pair structure which defines an allocation as an aircraft from its currently assigned runway to an available alternate runway. One of the factors in evaluation of a potential allocation is its effect on total system delay. In preparation for evaluation by the knowledge-based rules of the preliminary cycle, the schedule for each aircraft to each available runway is estimated.

The delay savings for each allocation is estimated as the difference in the sum of expected time to fly for all aircraft in the system for both the allocation and non-allocation cases. At this point, it is important to define what is used as the expected time to fly.

A time known as the nominal scheduled time of arrival (STA) is used as the reference for expected time to fly. Nominal STA is defined as the later of an aircraft's undelayed ETA (fastest possible trajectory) or the arrival time corresponding to minimum separation with the aircraft sequenced one ahead on final approach at the runway threshold.

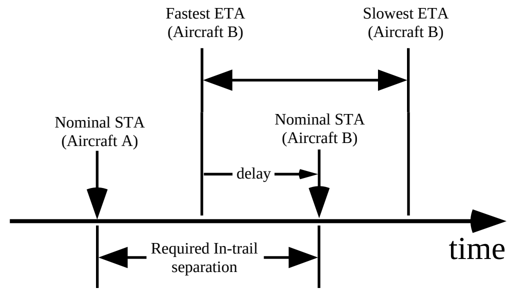

Figure 7. Nominal STA Derivation

As shown in Figure 7, Aircraft B would be in violation with Aircraft A if it were to meet its fastest ETA; therefore, its nominal STA is dependent upon the nominal STA of Aircraft A and the required minimum separation distance, governed by FAA regulations and based on aircraft type and winds aloft on final approach.

The nominal STA is used as the reference for two reasons: simplicity and accuracy. Simplicity is essential if the preliminary cycle is to achieve its goal of rapid evaluation of all potential allocations. Calculation of the nominal STAs require an established sequence on each final approach, each aircraft's ETA, and the weight class of each aircraft to determine required separation, as well as an assumption for ground speed on final approach. Each of these inputs has already been determined, and is easily accessible; leading to rapid estimation of total system flight time and delay savings for each allocation pair.

Producing an acceptable set of conflict-free 4D trajectories for all aircraft in the system is an extremely difficult task.[7] To produce such a solution set requires precise modeling of controller decision patterns, coordination and prioritization of tasks. Furthermore, it would require exactness in route deviation (and DOF) possibilities, and accurate modeling of how a controller employs these DOFs. This is largely accounted for in the FAST sequencing algorithm, however, it is too computationally intensive for the task described here. To simplify estimation of total flight time in the preliminary cycle, the allocation aircraft is sequenced First-Come-First-Served on the alternate runway. This allows for numerous estimations of delay savings to be made without revisiting the sequencing logic. For this reason, it is assumed that this model of the sequencing algorithm is sufficiently close to produce usable results in the preliminary cycle.

Knowledge-Based Decision Tree

Once the potential delay savings have been estimated in the preliminary cycle, each potential runway allocation is evaluated with a decision tree which incorporates the knowledge base of facility procedures, controller workload issues and delay reduction criteria. This decision tree determines if each potential allocation would achieve necessary delay benefits and would be acceptable to controllers. Figure 8 illustrates a simplified runway decision tree, showing a single thread of a series of branches. Each branch in the tree is based on the result of one of the rules presented in Appendix A. Individually these criteria represent simple, understandable ideas related to controller workload and delay reduction. In combination, however, they can adequately and efficiently represent the complex decision patterns of experienced terminal area controllers. For each potential allocation, a decision tree is traversed until a rule is evaluated which results in a decision to either allow further evaluation of the allocation (pass the preliminary cycle), or to remove it from the list of potential allocations (fail the preliminary cycle).

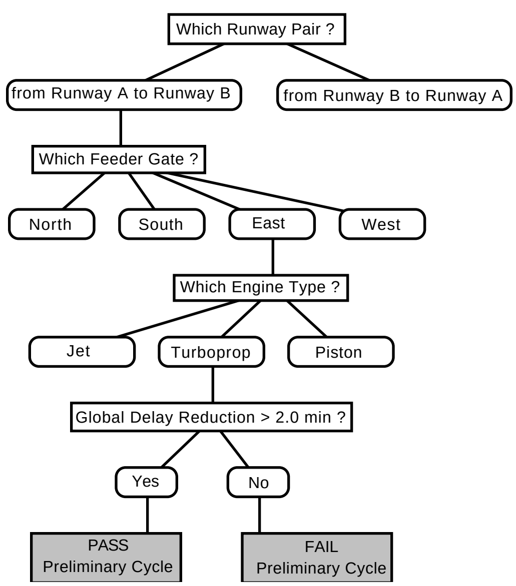

Figure 8. Sample Preliminary Evaluation Decision Tree

A list of potentially beneficial and acceptable allocations results from the preliminary evaluation cycle. This reduced set of allocations is further evaluated to insure delay benefits and controller acceptability in the final cycle.

Final Cycle

The final cycle of the FAST KBRA algorithm is essentially a preventative measure employed to fully evaluate the most promising allocation in the list of allocations which passed the short cycle rules. Inappropriate allocations are avoided by performing an in depth evaluation of one allocation pair per update cycle, as shown in Figure 9.

This greater depth of evaluation is accomplished by creating an alternate schedule which includes the candidate allocation aircraft to its alternate runway. The final cycle consists of five steps: selecting an allocation pair for evaluation, creating the alternate arrival plan, conflict detection/resolution for the alternate arrival plan, estimation of delay savings for the alternate arrival plan and evaluation of the candidate allocation pair with a knowledge-based criteria list.

The list of potentially beneficial and acceptable allocations from the preliminary cycle is sorted primarily by delay savings potential. Allocation pairs with similar delay savings potential are sorted based on

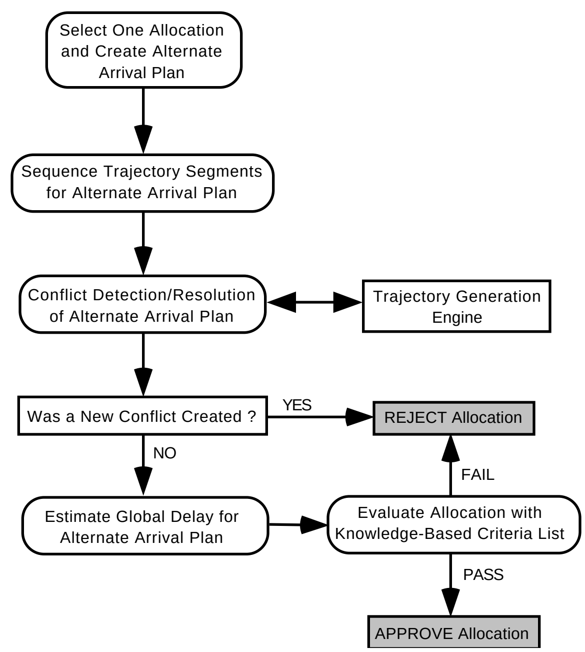

Figure 9. Final Cycle for Runway Allocation

elapsed time since the allocation pair was last selected for evaluation by the final cycle. Following sorting, the first allocation pair in the list is selected for in-depth evaluation.

An alternate arrival plan is created by revisiting the trajectory segment evaluation logic for the candidate allocation aircraft. Once the trajectory to the alternate runway has been dissected into segments, the knowledge based sequencing (KBS) algorithm sequences the alternate arrival plan in the same manner as was used for the current arrival plan.[7] Sequencing the alternate arrival plan produces a more realistic schedule than that which was used in the preliminary cycle. The preliminary cycle simply placed the candidate allocation aircraft first-come-first-serve on its alternate runway. Sequencing in the final cycle takes into account merging streams of aircraft and controller workload in its knowledge base. It is possible that the sequence on any trajectory segment in the system could change, not only the sequence on the segments which the allocation aircraft traverses.

As a minimum requirement for an allocation to be acceptable, it must not adversely affect the conflict resolution status of the aircraft. In other words, if the candidate allocation aircraft is conflict-free on the default runway, but predicted to be in conflict on the alternate runway, the allocation is assumed unacceptable from a controller workload standpoint. A conflict occurs when an aircraft does not have enough delay absorption capability, as defined in the route adaptation, to resolve a predicted separation violation. Regardless of any predicted delay savings (based on nominal STAs), FAST will not advise an allocation which, because of a new conflict, may unacceptably increase controller workload.

If an allocation passes the conflict resolution criterion, its delay savings must be recalculated. Because nominal STAs depend on the sequence of aircraft, they may differ from the STAs predicted in the preliminary cycle. For this reason, the delay savings estimate may not be the same for the final cycle as for the preliminary cycle. The new delay savings estimate is stored for further evaluation by the final cycle.

Evaluation of the candidate allocation pair by the final cycle is accomplished through a criteria list. This list is a set of criteria specific to the allocation being evaluated. A list exists for each runway pair/category combination. As shown by Figure 10, the criteria in the list are evaluated either until a criterion is not met, or until all criteria are satisfied. If all criteria are satisfied, the candidate runway allocation is advised to the controller. If any one of the criteria are not satisfied, the final determination cycle rejects the candidate allocation, and in most cases the current arrival plan is maintained.

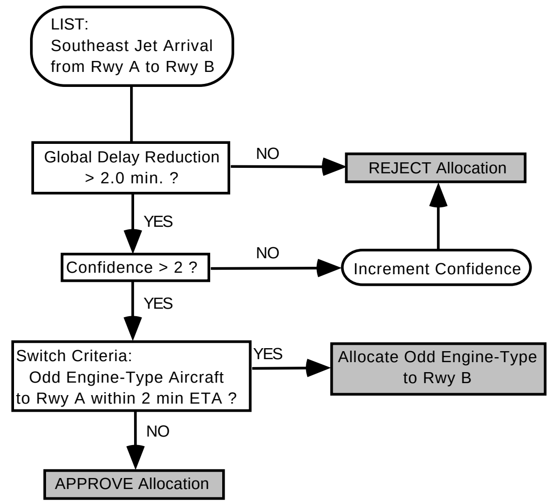

Figure 10. Example Final Cycle Criteria List

The criteria used in the lists are presented in Appendix B. However, the roles of two criteria should briefly be discussed here. The “confidence” criterion simply increments a counter for a given allocation pair, and will not let an allocation occur until the counter reaches an adaptation specified value. The confidence level criterion prevents improper allocations resulting from various errors (variable ETA or radar data, etc.). As a result of the confidence criterion, aircraft which enter the preliminary cycle’s allocation time window first, are more likely to satisfy the confidence criterion before those with slightly later ETAs. This may not always lead to the most acceptable allocation.

When the candidate allocation satisfies the confidence criterion, “switch” criteria can be used to search for more appropriate allocations which would serve the same general purpose as the candidate allocation. If an aircraft is found which would yield a more acceptable allocation, the final cycle rejects the candidate allocation, and advises controllers of the more acceptable allocation.

Operational Test Results

FAST was evaluated operationally at the Dallas/Fort Worth TRACON during 1996.[8] FAST was operational for over twenty arrival rushes spanning the spectrum of nearly all traffic patterns encountered at DFW TRACON. During these arrival rushes, controllers evaluated FAST generated sequence and runway advisories for over 1200 arrivals. Both controller feedback and statistical trends indicate the expected benefits were realized.[8]

The TRACON traffic management coordinator (TMC) routinely increased the acceptance rate during FAST tests to levels above normal operations. This indicates that controllers were able to handle aircraft more efficiently; leading to more operations at similar workload. As shown in Figure 11, airport throughput was increased 9.3% during IFR operations and 13.3% during VFR operations with FAST.[8]

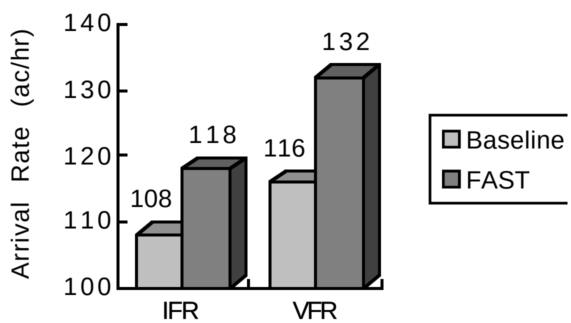

Figure 11. Comparison of mean airport throughput during peak portion of 11:15 am rushes.[8]

Comments from tower controllers were overwhelmingly positive. The departure queue backlog was reduced by 9% due to well-balanced runways and consistently-spaced arrivals. Tower operations logs showed an average increase of 28 operations per hour or approx. 13% (15 arrivals & 13 departures) during rushes in which FAST was operating. Taxi-in and taxi-out times were not impacted despite capacity increases.[8]

Controller feedback through post-rush evaluation forms, modeled after the NASA Task Load Index (TLX) scale, indicated no significant impact on overall controller workload due to the use of Passive FAST.[8] A modified Controller Acceptance Rating Scale (CARS) was used to gauge overall system acceptability. CARS responses indicated the prototype FAST system needed minor modifications to become fully acceptable. Comments from the CARS forms stated the major concerns with runway allocation performance of FAST were late runway allocations and response time to controller inputs. Late allocations could be avoided by sliding the runway allocation eligibility window further from landing time, thus improving perceived schedule stability. Response to controller input has been improved by employing faster computers for FAST.

Advisory adherence can be used to gauge acceptability of FAST-generated advisories. Controllers had the option to override any advisory judged to be unsafe, sub-optimal, high-workload or generally unacceptable for any reason.

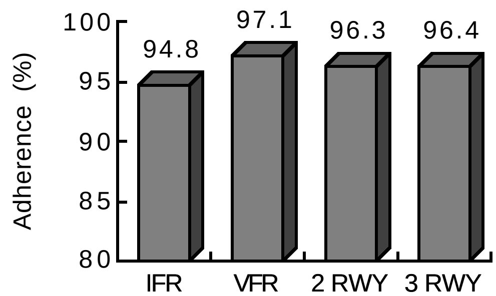

Figure 12: Adherence to FAST Runway Advisories

Non-adherence to a large number of advisories could lead to increased controller workload, reduced benefits, and distrust of the system. While controllers disagreed with some of the runway advisories, overall adherence to runway advisories was high, indicating trust in the system (Fig. 12).

Conclusions

A knowledge-based system for sequencing and assigning runways to arrival traffic to the terminal area has been developed and tested. The algorithms and knowledge base were developed through thousands of hours of controller-in-the-loop simulation. Field testing of FAST has demonstrated the ability of a limited number of rules to adequately model the runway assignment decision process. While this set of rules may need to be expanded for other airspaces (e.g. Chicago, New York), the ability to model the runway assignment decision process with a limited rule-base has been demonstrated.

The knowledge-based runway allocation (KBRA) algorithm uses the results of the knowledge-based sequencing algorithm, in a two-cycled approach. The preliminary cycle quickly evaluates all eligible re-assignments for potential benefits and controller acceptability. The preliminary cycle reduces the number of potential reassignments to a manageable number for further evaluation. The final cycle evaluates this reduced set and selects one re-assignment for in-depth evaluation. This candidate re-assignment is verified to achieve the required benefits and acceptability requirements established by the knowledge base.

Operational testing at Dallas/Fort Worth TRACON has demonstrated significant increases in airport capacity without adversely affecting controller workload. The tests also indicated reduced departure delays are possible due to runway balancing and reduced ground congestion. As a result of the benefits demonstrated through testing and evaluation of the prototype system, an operational version of FAST is now scheduled for deployment in 5 to 10 major U.S. airports.

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Appendix A - Rules used for Preliminary Runway Allocation Evaluation

The rules in this appendix are used in the decision trees of the preliminary evaluation cycle. While the number of rules presented here is brief, they were found completely able to adequately model runway allocation decision patterns when used in combination. Air traffic systems and facility procedures are varied, and may require development of more rules to solve problems unique to each facility. Eight rules were used in developing the decision trees for the DFW TRACON. The logic behind each rule will be discussed, as well as its input, basis in controller decision patterns, and usage.

AC IN CATEGORY EXISTS: This rule determines if any aircraft in a specified runway category exist in the system. The runway category is determined from the feeder gate, airport configuration, destination, and engine type. The existence of an aircraft in the specified runway category could affect the acceptability of an allocation.

WHICH ENGINE: This rule determines the aircraft engine type: jet, turboprop, or piston. Certain allocations are preferred for a given engine type over others. This is due to TRACON routing, which separates aircraft by stream class as they arrive over the feeder gate.

FEEDER GATE RUSH: This rule is used to recognize when a large number of aircraft are to arrive through a single feeder gate and are scheduled to a single runway. Without allocation, a feeder gate rush leads to unacceptable workload and high delay. This can be avoided by recognizing this situation before this group of aircraft reach the feeder gate, and allocating from this group to alternate runways.

WHICH RUNWAY CATEGORY: This rule determines if the aircraft being evaluated by a decision tree is of the runway category specified by the decision tree. The factors determining runway category are often used in favoring one group of aircraft for allocation over another. This rule is commonly used in a similar fashion to the engine type rule, but can be expanded to employ runway categories that are dependent on airport configuration and common operating procedures.

ODD AC TYPE: It is common practice for controllers to stratify a traffic flow based on engine type. Controllers prefer to maintain stream consistency (engine type) whenever possible. Aircraft of similar engine type generally have similar performance characteristics. This leads to repeatability of commands and lowers the workload associated with maintaining separation in a traffic stream. This predicates allocations based on engine type. However, the engine type such an allocation is based on varies depending on the mix of aircraft in the stream from which an allocation will come. For this reason, it is necessary to recognize when an odd-type aircraft is in a traffic stream. An odd type aircraft is defined as an aircraft whose engine type consists of less than 43% of the stream being considered.

RUNWAY BUSY: This rule counts the number of aircraft assigned to a given runway within a specified time window of the evaluation aircraft's ETA on that runway, to determine if a runway will be busy at the time of the evaluation aircraft's ETA. This rule is linked to controller workload and is employed to incorporate controller workload in the knowledge base. Used alone, it could set a limit on the number of aircraft allowed to be assigned (by FAST) to a given runway. However, it is usually grouped to form numerous branches with varying delay threshold values, based on how busy a runway is. Furthermore, nesting of runway busy rules increases flexibility by allowing a "tradeoff" of delay to be used in determining if an allocation is acceptable. Unlike "feeder gate rush", "runway busy" counts all aircraft to a given runway in the specified time window, not just those arriving over a single feeder gate.

DELAY REDUCTION: Delay reduction is employed as a rule that usually is the final rule used to determine eligibility for the long cycle. It is not required that delay be reduced for an allocation to pass the preliminary cycle rules. If workload issues warrant an allocation, one could be made which increases delay: as long as the amount by which the delay is increased is less than that specified in the decision tree. Situations which could lead to such an allocation are captured in the decision tree by the previously described rules.

RUNWAY AVAILABLE WITH NO DELAY:
While delay reduction is a measure of the savings in total flight time of all aircraft in the system, it is not necessarily the basis for controller preferred allocations. This rule determines if the allocation under evaluation would lead to delay for any aircraft assigned to the alternate runway. Regardless of prescribed configuration and default runway, situations exist in which controllers prefer an alternate runway over the default if such an allocation does not affect any other aircraft on the new runway (no added delay). This effectively removes any flight time difference from the delay estimation. For example, it may be preferred by the controller or the airline to land on the parallel runway as opposed to a diagonal runway due to perceived taxi time, if such an allocation does not add delay to any other aircraft.

Appendix B - Criteria used for Final Runway Allocation Determination

These criteria are used by the final cycle to evaluate the acceptability of the candidate allocation. Some of the criteria are very similar to the rules used in the preliminary evaluation decision trees. However, these criteria are evaluated following KBS sequencing of the alternate arrival plan. This could lead to different delay savings estimates and controller acceptability. Each of the five long cycle criteria, their input and usage will now be discussed.

USE RUNWAY IF DELAY REDUCED: The delay reduction threshold required for the long cycle can be explicitly specified in the adaptation, but is generally set to the same value as specified in the preliminary cycle. Used in this manner, this criterion simply verifies that the delay savings estimated in the preliminary cycle, are still realized following KBS sequencing of the alternate arrival plan.

USE RWY IF AVAIL WITH NO DELAY: Also similar to the rule used in the preliminary cycle, this criterion is generally used as a verification of delay estimates of the short cycle.

CHECK CONFIDENCE LEVEL: This criterion is used in a manner consistent with a low pass filter. Only those allocations which have consistently passed the previous criteria in the list achieve the required confidence, thus stabilizing the runway allocation process. Each time an allocation reaches the confidence criterion, its confidence level is incremented. Once an allocation achieves the required confidence level, this criterion is satisfied. The confidence level of allocations can be reset by the criteria if an allocation is advised.

"Switch" criteria: Switch criteria are used after an aircraft has been determined to meet the confidence level required, along with all other criteria employed. The purpose of a switch criteria is to search the specified traffic stream for a more suitable aircraft for allocation. Switch criteria are means of enforcing controller preferences in the long cycle for allocations which may be acceptable but not the most acceptable. Once a switch criteria has been reached in the criteria list, the candidate allocation has been deemed acceptable. For that reason, once a switch criterion has been reached, an allocation will occur, but the candidate allocation may be replaced with a similar allocation considered more acceptable to controllers. Two switch criteria are employed: one concerning runway category preference, and the other employing the odd engine type logic similar to that of preliminary cycle.

SWITCH RUNWAY WITH OTHER CATEGORY: This criterion searches the system for aircraft within the specified time window in the specified runway category which would be a more acceptable allocation than the one determined to meet all previous criteria in the list. This criterion can be used to model general controller decision patterns for runway allocation once it has been determined an allocation is necessary for a given time or runway slot. Choosing the most acceptable aircraft to fill that slot, or balance runways, can be achieved by defining preferred runway categories for each allocation pair considered.

SWITCH RWY WITH ODD AC TYPE: Again, this switch criteria is a means of insuring the most acceptable allocation of a given type is advised. Similar to the short cycle odd engine type logic, this criterion searches the stream of the candidate allocation aircraft for an aircraft of odd engine type, if the candidate aircraft is not of an odd type in the stream. This criteria is necessary due to the cyclical nature of the runway allocation process. The runway allocation cycle only occurs once every update cycle (6.0 seconds). This determines that allocations of similar benefit are evaluated in turn as they enter the allocation window. This fact, coupled with the confidence criterion, means the earlier an aircraft enters the allocation time window, the better chance it has of being allocated. Such behavior does not always lead to the most acceptable allocation. The switch criteria corrects for this cyclical nature by determining if there are any other aircraft in the system which would closely match the candidate allocation, yet be more acceptable to controllers.