In early 1989, the system operations control center at American Airlines implemented a network-optimization-based system to help reduce delays imposed by air traffic control. The Arrival Slot Allocation System (ASAS) is an interactive decision support tool that uses a network-based heuristic to help flight dispatch personnel take advantage of flight cancellations to re-schedule arrivals into an airport. When bad weather or other unpredictable factors reduce the capacity of the airport or airspace for traffic, the Federal Aviation Administration employs ground-delay programs to hold aircraft at their originating cities. These delays affect airline dependability statistics adversely and inconvenience passengers. In recent years, air traffic control has developed slot-substitution rules that allow airlines to use the arrival slots of canceled flights to reduce delays created by the ground-delay programs. In one year, using ASAS the system operations control center reduced the delays imposed by air traffic control by approximately 345,000 minutes. This translates into $5.2 million savings in direct operating costs for the airline. ASAS also improved dependability statistics for American Airlines by an average of two percent per ground-delay program.
American Airlines’ operating route network is based on a hub-and-spoke system consisting of seven hubs: the largest being Dallas/Fort Worth, Texas; followed by Chicago, Illinois; Raleigh-Durham, North Carolina; Nashville, Tennessee; San Jose, California; San Juan, Puerto Rico; and Miami, Florida. American has the largest fleet among the western-world airlines with more than 500 aircraft that fly over 2,400 daily flight segments (city pairs) and provide transportation service to over 160 cities worldwide, including destinations in Europe, the Orient, the South Pacific, and South America.

The responsibility of implementing American Airlines’ schedule on a day-to-day basis rests with the system operations control center, located at the American Airlines headquarters complex near the Dallas/Fort Worth International Airport. Here, a group of highly coordinated and trained people perform the flight dispatch function that monitors and controls American Airlines’ worldwide operations so that American has the largest fleet among the western-world airlines.

Adding service to more international and domestic destinations. It expects to purchase as many as 500 new aircraft during the next five to ten years, about half of them to replace less efficient and noisier airplanes. The airline will also need appropriate control and rescheduling tools to prevent unnecessary costs, especially during bad weather when unforeseeable events interfere with regular operations. Recently, system operations control implemented ASAS to help flight dispatchers to reschedule arrivals into airports whose airspace capacity is temporarily limited. **Rescheduling of American Airlines’ Resources**

Rescheduling airline resources and activities during poor weather or abnormal conditions is the biggest challenge for system operations control, which must coordinate the operational departments that help American Airlines to meet its commitment to on-time service. Such rescheduling problems arise when central flow control, a facility of the air traffic control system, employs ground-delay programs to match the arriving flight demand to the reduced capacity at airports. These delay programs tend to be more frequent during the winter months, when bad weather is more common, and a single airport may be affected by up to five delay programs in one day.

Flight dispatchers must interact with the central flow control facility, an operating center in Washington, DC that is responsible for monitoring and managing the flow of air traffic on a daily basis. The central flow control facility and the domestic air route traffic control centers spread throughout the United States constantly monitor the weather and other factors that
may reduce the capacity of airports to handle all traffic. Bad weather reduces visibility, and under low visibility conditions, the operating requirements for aircraft in the airport traffic area change from visual flight rules (VFR) to instrument flight rules (IFR). During VFR flight, pilots help to monitor their own separation from other aircraft; in IFR flight, pilots use flight instruments, and for safety purposes aircraft must be separated by greater distances.

This increased separation reduces the airport’s traffic capacity, which translates into a low arrival rate; the rate is determined and regulated by the central flow control facility. Reduced airspace capacity displaces arriving flights to later times in the day and soon extends the delay effects to other arriving flights (Figure 1). Central flow control analyzes the effects of the reduced arrival rate, identifies the specific flights that must be delayed, and proposes

Figure 1: A ground-delay program creates a rescheduling effect on arriving flights at Chicago O’Hare International Airport. Under visual flight rule (VFR) operations, O’Hare’s capacity is approximately eight arrivals every five minutes. Under instrument flight rules (IFR), O’Hare’s capacity is reduced to approximately five arrivals every five minutes. Flights scheduled to arrive above the IFR capacity line, like flight 281 (scheduled to arrive at 16:32), must be rescheduled to a later arrival time (17:32 is flight 281’s original-controlled arrival time).
to each airline’s system operations control center a rescheduled time of arrival (and consequently a rescheduled time of departure from the flights’ originating cities) through a ground-delay program.

**Rippling Effects of Delays**

In general, delays propagate quickly through the airlines’ service network and generate multiple inconveniences for passengers who end up spending extra time at airports, missing their flight connections or losing their bags. Delays also affect later flights that rely on using the delayed aircraft, crew, and gates later in the day. If the delay continues to affect flights through the night, it may affect the next day’s scheduled operations, since several aircraft maintenance checks must be performed overnight and crew members require a minimum rest period between working days. Cockpit crew members (pilot, first officer, and flight engineer) and cabin crew members (flight attendants) assigned to delayed flights may also reach the legal time limits imposed by their union contracts and therefore be unable to fly all the flights for which they are scheduled. Delays also have a negative effect on customers’ perception of the airline. This loss of “goodwill” (a measure of the quality of airline service from the passengers’ standpoint) is not limited to the travelers directly affected by delays, but extends to those who have access to the dependability records published every month by the Department of Transportation. At American Airlines, management has increasingly emphasized on-time performance because of the positive impact that a reliable schedule has on future airline business.

American Airlines has felt the effects of ground-delay programs throughout its service network for several years. These delays have been handled according to the normal procedures developed by system operations control personnel that sometimes allow delays to dampen out by using slack connect time built into the scheduled aircraft connections at airports. For example, an aircraft arriving at Chicago O’Hare needs to spend a minimum of 35 minutes on the ground for catering, fueling, and cleaning, but the schedule provides 53 minutes on the ground. Hence, 18 minutes of slack time are available (53 minutes minus 35 minutes) before the aircraft departs on the next flight. If the incoming flight is delayed by a ground-delay program for 60 minutes, the slack connect time of 18 minutes decreases the delay of the aircraft’s outbound flight to 42 minutes. Delays tend to have down-line rippling effects on many other flights often for several hours until the slack connect time built into the aircraft’s routing can dampen the propagating delay effect to zero. A similar delay propagation effect is generated by crew connections.

Flight dispatchers use control techniques to prevent the propagation of delays through the schedule; for instance, they take advantage of multiple aircraft connections at airports to reassign inbound aircraft among outbound flights. When no opportunity for reassigning aircraft exists,
however, dispatchers may have to cancel outbound flights (whose passengers can be transferred to other flights) to equate the number of departing flights to the number of aircraft available, and to reassign the canceled flights’ aircraft to flights with large delays that can then depart on time.

**Opportunities to Reduce Ground Delays**

In the last 10 years, the airline industry has grown rapidly, motivated by the deregulation act of 1978. The volume of traffic traveling through the national air space network has increased by about 30 percent since deregulation, placing higher operating demands on major US airports—a trend that is likely to continue as demand for air travel continues to rise. Due to the increase in airport traffic, the central flow control facility has gradually increased its use of ground-delay programs to control aircraft flow in the vicinity of airports, making ground-delay programs a daily phenomenon in airline operations.

Air traffic control realized this fact and devised a system to allow airlines to manage the arrival slots freed by cancellations during ground-delay programs.

A ground-delay program includes six types of information concerning each flight affected: the arrival airport, the flight number, the departure airport, the scheduled departure time, the rescheduled (also called controlled) time of departure, and the rescheduled (controlled) time of arrival (Table 1).

The rules for managing ground-delay programs use the concept of an arrival slot as a window of time when an aircraft can land at an airport. During enforcement of a ground-delay program, an arrival slot for each flight runs from a minutes before the controlled (or rescheduled) arrival time to b minutes after the controlled arrival time (a and b are parameters subject to change by air traffic control provided that carriers are properly notified). For the results reported in this paper a and b are both equal to 20 minutes.

To explain the slot substitution rules stated by air traffic control, I must define some terminology: a canceled flight empties an arrival slot, and some other flights contained in the ground-delay program may be moved into the free slot; these flights are called substitution candidates; when one of these candidates moves into the empty slot, it leaves behind a replacement empty slot that has a new set of substitution candidates. This alternating sequence of moving a substitution candidate into an empty replacement slot and leaving behind a different empty replacement slot pro-

<table>
<thead>
<tr>
<th>Flight Number</th>
<th>Departure Airport</th>
<th>Scheduled Departure</th>
<th>Controlled Departure</th>
<th>Scheduled Arrival</th>
<th>Controlled Arrival</th>
</tr>
</thead>
<tbody>
<tr>
<td>AAL235</td>
<td>EWR</td>
<td>14:03</td>
<td>14:52</td>
<td>16:21</td>
<td>17:10</td>
</tr>
<tr>
<td>AAL281</td>
<td>BOS</td>
<td>13:40</td>
<td>14:40</td>
<td>16:32</td>
<td>17:32</td>
</tr>
<tr>
<td>AAL337</td>
<td>FWA</td>
<td>15:37</td>
<td>16:47</td>
<td>16:23</td>
<td>17:33</td>
</tr>
</tbody>
</table>

Table 1: Information contained in a ground-delay program for Chicago O’Hare (ORD) affecting three flights on Sunday, January 14, 1990: flight 235 from Newark (EWR), flight 281 from Boston (BOS), and flight 337 from Fort Wayne (FWA). The rescheduled departure and arrival times are called original-controlled departure and arrival times respectively. All times are expressed in Greenwich mean time.
ceeds until no more candidates are found for the currently empty slot. The slot substitution process allows the airline to use a minimum number of flight cancellations (one in most cases) to reduce the delay of several flights. The slot substitution rules allow the airline to propose a new (also called revised) controlled arrival time that is as close as possible to the scheduled arrival time of each substitute flight (Figure 2).

Central flow control enforces the following rules for managing arrival slots at airports operating at reduced capacity:

1. Perform arrival slot substitutions only between two flights of the same company.
2. Allow an arrival slot substitution only if the revised controlled time of arrival for the substitute flight is within the arrival slot of the canceled or replaced flight.
3. Allow only substitutions that save more than 10 minutes of delay.

These rules allow carriers to manage arrival slots at their convenience when

Figure 2: The relationship between scheduled, original-controlled, and revised-controlled times defines the feasible space on which the slot allocation process must be performed. The arrival slots are defined as running 20 minutes before and after the controlled times of arrival. Cancelled flight 235 empties a slot, substitute flight 281 moves into the empty slot leaving behind an empty replacement slot that can be used by flight 337.
mechanical problems cause flights to be canceled. System operations control recognized the potential advantages of these rules for American Airlines and developed a set of procedures to manage ground-delay programs.

**Operational Procedures for Ground-Delay Programs**

The process of allocating arrival slots starts when a teletype message from central flow control is sent through a direct communication link from air traffic control’s computer system in Washington, DC to American Airlines’ computer system in Tulsa, Oklahoma. The message is printed out at American’s system operations control center in Dallas/Fort Worth, Texas, making the manager on duty aware of the delay of flights scheduled to arrive at the affected airport.

A dispatcher transfers the delay data to a worksheet containing the scheduled times and the proposed rescheduled times. Then, the dispatcher performs the calculations necessary to allocate arrival slots by applying the substitution rules. Complex computations are required to find a satisfactory solution for allocating arrival slots. After the dispatcher is satisfied with the results, he sends back to central flow control the following information for each flight: the scheduled time of departure; the “original” controlled time of departure (specified in the ground-delay program message from central flow control); the “revised” controlled time of departure (to be proposed to central flow control); and the “original” and “revised” delays.

The dispatcher in charge of the analysis waits for confirmation from the central flow control facility, acknowledging the acceptance or rejection of the revised-controlled times. If the times are accepted, the dispatcher distributes the message to all dispatch desks responsible for controlling and monitoring flight departures. However, if the revised times are rejected, the dispatcher must repeat the entire analysis, but this time he must disregard flight segments that had a scheduled departure time earlier than a threshold time value. The dispatcher sets this threshold time (usually 15 minutes after current clock reading) to have enough time to reanalyze the scheduled and revised times contained in the program, repeat the slot allocation process, and send a different set of revised-controlled times to central flow control (Figure 3).

Rescheduling arriving flights at an airport by allocating arrival slots minimizes delays at that airport and their rippling delay effects through the system. The arrival slot allocation process helps the airline to fulfill its primary operating goal: provide safe, on-time service to passengers to show American Airlines commitment to quality in spite of unpredictable reductions in airspace capacity. If American Airlines ability to provide this quality service is reduced, flight dispatch, in coordination with all other operational departments of the airline, will cancel flights to make room for the substitutions needed to meet the schedule. It chooses which flights to cancel, canceling those that affect the minimum number of passengers (who can usually be transferred to other flights or compensated by the airline in some other way). The benefit is providing better service to a larger number of passengers. But, accomplishing this objective is not easy. Flight
Figure 3: The slot substitution process begins when (1) a ground-delay program arrives from central flow control. (2) The manager on duty at the operations control center becomes aware of the message and (3) a dispatcher transfers delay data to a work sheet. (4) Slots are allocated. (5) A response is sent to central flow control. (6) A confirmation is received from central flow control. (7) If central flow control accepts the revised departure and arrival times, the message giving the new slot allocations is distributed to all dispatch desks affected. (8) If central flow control rejects the proposed revised times, processes (4), (5), and (6) must be repeated.

dispatchers must weigh the multiple and sometimes conflicting objectives established by the airline's different operating departments. For instance, passenger service representatives at each airport demand on-time dependable service; managers on duty at the maintenance operations control center, located at Tulsa, Oklahoma, must insure that aircraft are serviced overnight at appropriate maintenance airports; crew schedules and crew tracking personnel, located in the same site as system operations control, must ensure that crew legalities are met; and airport managers must avoid gate conflicts among arriving and departing aircraft to insure that passengers do not miss their connections.

**Manual Solution Attempts**

System operation control recognized the opportunity for savings that an arrival slot allocation process could have on the entire operation of American Airlines and started
a manual procedure that was first tested at San Francisco International Airport, where each delay program affects only a few flight segments (an average of 15 flights per program). The results were encouraging; they confirmed that management’s expectations on delay savings could be accomplished even though dispatchers could

The benefit is providing better service to a larger number of passengers.

find only one feasible allocation of slots per program because they had to perform such a large number of computations. The success at San Francisco motivated system operations control management to attempt manual solutions of delay programs for Chicago O’Hare (American’s second largest hub), but the results were discouraging. System operations control management immediately recognized the complexity of the problem and the limitations of the manual process, which sometimes required three people to work for three hours to solve O’Hare’s programs. Several times, after intense and lengthy work, the dispatchers learned that their solutions had been rejected by the central flow control facility because of the long time it had taken them to solve a problem.

One alternative was to hire and dedicate more people to the manual process, but in early 1988, system operations control management anticipated that department budget constraints would limit its ability to hire an estimated seven more dispatchers needed to work on ground-delay programs. The situation was worsened by the lack of qualified flight dispatch personnel in the job market. Management looked to computer automation as an alternative to overcome these obstacles and created a task group to recommend hardware platforms and to identify automation opportunities. The task force and the data-processing department at American Airlines proposed using microcomputers and local area networks as the hardware system platform that could satisfy system operations control’s automation needs. A local area network was installed in the spring of 1988, and a local data-base system containing all scheduled and current flight information was installed in the summer of 1988.

The limitations of the manual slot allocation process created the need for an automated system capable of solving ground-delay programs for any airport in American Airlines’ service network, including the largest hubs: Dallas/Fort Worth with about 400 daily arrivals and Chicago O’Hare with about 350.

Automated Arrival Slot Allocation

In late August 1988, system operations control expressed its need for an automated arrival slot allocation system and American Airlines Decision Technologies agreed to develop it in the microcomputer environment. The challenge was to build an integrated and automated system on top of the manual procedures to allocate arrival slots. Evidently, the bottleneck steps in the slot allocation process were the retrieval of delay data, the allocation of arrival slots, and the transmission of the revised departure and arrival times to central flow control. It was also evident that management science techniques could help the most in allocating arrival slots.
The objective in developing ASAS was to create an integrated system that would
(1) Allocate arrival slots efficiently, minimizing the amount of delays from
ground-delay programs;
(2) Provide an environment to automate the calculation of delay times and the
transmission of results with minimum user intervention;
(3) Give dispatchers more time to perform their everyday activities by turning out
results quickly (in a matter of seconds) and allow dispatchers time to play sev-
nal what-if scenarios before committing to a solution;
(4) Be flexible enough to allow dispatchers to alter the computer generated solu-
tion easily and quickly.

In addition, ASAS should be highly responsive to ground delays of any size af-
f ecting any airport, and it should accept revisions to ground-delay programs while in
the middle of an analysis because central flow control frequently revises its delay
messages, increasing or decreasing delays as weather patterns change at the affected
airports.

The system had to be flexible so that dispatchers could fine-tune slot allocations to
handle exceptional cases where they had more information than the computer about a
particular situation. The user interface had to provide advice to dispatchers and
receive their input about the state of the airline. The system also had to allow dis-
patchers to backtrack on a solution path, look at the feasible options at that point,
perform local adjustments to substitutions, and ask the computer to generate the rest
of the solution without having to start from the beginning.

Following these guidelines, I defined the structure of the system. It consists of two
components: an optimization algorithm that minimizes the amount of delay by
taking advantage of flight cancellations created mainly by mechanical problems;
and a data-processing component that cuts down the overall turnaround time of re-
sponses to central flow control by automating the processes of sending and receiving
messages.

**ASAS Functional Modules**

ASAS consists of four integrated mod-
ules: data integration, heuristic allocation
of arrival slots, fine tuning of results to
consolidate multiple operating policies, and
automatic transmission of results for ap-
proval (Figure 4).

**Module 1—Data Integration**

The data-integration module reduces the
amount of time required to process the in-
put data used in the slot allocation process.
The data base residing in the local area
network contains the latest information
about the state of the airline operations.
Dispatchers can use ASAS to create sched-
ule scenarios by extracting information
from this data base on all flight segments
arriving into a specific airport, such as
flight numbers, scheduled departure and
arrival times, number of passengers, equip-
ment type, the airport from which the
flight segment originates, and profile infor-
mation on flight cancellation.

When the system operations control cen-
ter receives a delay program, the manager
on duty is informed, and a dispatcher uses
ASAS capabilities to access the main data
base to retrieve the delay program and
make it available in the local environment.
ASAS allows the dispatcher to
automatically merge the schedule data for the affected airport with the information contained in the delay program to provide the delay factor for each flight segment and the original-controlled departure and arrival times.

Module 2—Heuristic Allocation of Arrival Slots

The air traffic control rules for performing slot substitutions allow ASAS to define the feasible region where the heuristic algorithm must be applied. ASAS takes ad-
vantage of delays and cancellations on specific flight segments to reduce the delays imposed by ground-delay programs on all other flights. The mathematical formulation of the problem is called the Arrival Slot Allocation Model (ASAM) and is designed to minimize the total inconvenience to passengers among all flights arriving at an airport affected by a ground-delay program. The model's objective minimizes a weighted function that measures passenger-minutes of delay (appendix).

The constraints of the problem relate to the definition of the feasible set of substitutions according to air traffic control rules:
(1) an arrival slot of a canceled or replaced flight segment can be used by only one substitute flight segment; (2) a substitute flight segment can occupy only one arrival slot of a canceled or replaced flight; (3) each flight must be allocated an empty arrival slot; (4) the revised-controlled arrival time of a substitute flight has to be within the arrival slot of the canceled or replaced flight; (5) the revised-controlled arrival time of a substitute flight segment has to be earlier than the original-controlled time of arrival imposed by central flow control; (6) the revised-controlled arrival time of a substitute flight segment cannot be earlier than its scheduled arrival time.

Module 3—Fine Tuning the Results

The flexibility in ASAS allows for immediate response in the fine-tuning process. Dispatchers can automatically run the model and obtain a solution that minimizes passenger inconvenience. If they have a flight segment that requires special treatment, they can interactively break at any point (including the cancellations) the computer-generated solution of any substitution sequence, observe the feasible set of moves at that point, perform a couple of manual substitutions if desired, and finally ask ASAM to generate the rest of the solution automatically.

The interactive solution allows dispatchers to use their knowledge about the status of the schedule to influence the resulting solution according to their understanding of the actual state of the airline. Dispatchers can exclude substitution calculations on certain flight segments by either accepting the imposed delays or explicitly avoiding an undesired slot substitution.

Module 4—Automatic Reply

The last module simplifies the communication of results to the central flow control facility. During the implementation of the model, it became evident that its efficient solution of the slot allocation problem would not be enough to obtain its acceptance. A bottleneck still existed in the process of sending responses to central flow control. Many of the frustrations experienced during the manual solution process were eliminated by the ASAS automated response procedures that successfully reduced the time required to complete the whole process.

I attribute the success of ASAS in the difficult arena of real-time operations to two important features of the model: it allows dispatchers to generate fast solutions to complicated problems, and it allows dispatchers to override those solutions without compromising the parts of the analysis that they have already accepted. The result is a truly interactive model that creates timely and efficient solutions to the slot allocation problem.
ASAM Structure and Previous Research

The centerpiece of ASAS, where the real value of the management science application lies, is the arrival slot allocation model. The first three constraints of the problem correspond to the resource-sequencing problem; in this case, the resource is a "wandering" arrival slot created by a flight cancellation. This problem is described in Baker [1974] as a sequence-dependent setup time problem, and it is directly associated with the directed traveling salesman problem [Lawler, Lenstra, and Rinnooy Kan 1985]. In the context of arrival slot allocation, each flight segment can be represented as a node in a network; the salesman has to visit each node, deliver one commodity (a free slot) in each visit, and create a tour through the network. The order of the nodes in the salesman’s tour corresponds to the sequence of arrival slot substitutions available for each empty slot.

To understand this concept, consider again the ground-delay program for Chicago O’Hare on January 14 (Table 1). Assume that the number of passengers is the same in all flights so that we can concentrate our attention only on the number of delay minutes saved. Provided that flight 235 is canceled because of a mechanical problem, its arrival slot at Chicago becomes free for substituting any other arriving flight. The empty slot starts at 16:50 and extends until 17:30. Therefore, according to the substitution rules, any other flight segment whose scheduled arrival time is earlier than 17:30 and whose controlled arrival time is later than 16:50 becomes a substitution candidate. If the scheduled arrival time is within the arrival slot, then the substitute flight can arrive on time. If the scheduled arrival time is earlier than 16:50, then the flight arrives with a smaller delay than the one imposed by central flow control. In the example, flight segments 281 and 337 have a scheduled arrival earlier than 16:50, and therefore, both become substitution candidates with a revised arrival time of 16:50. If substituted, their new delays would be 18 minutes for flight 281 or 27 minutes for flight 337.

If flight 281 is substituted for flight 235, its original controlled arrival slot from 17:12 to 17:52 becomes available for flight segment 337, which can then arrive at 17:12 with a new delay time of 49 minutes. On the other hand, if flight 337 is substituted for flight 235, its arrival slot from 17:13 to 17:53 becomes available for flight 281, which can then arrive at 17:13 with a delay of 41 minutes instead of 60 minutes (Figure 5). In this case there are two possible tours for the traveling salesman to traverse: the first tour is the sequence that starts with the cancellation of flight 235, followed by the substitutions of flights 281 and 337 for a total delay of 67 minutes; the second tour is the sequence that starts also with the cancellation of flight 235 followed by the substitutions of flights 337 and 281 for a total delay of 68 minutes. In this case, the heuristic built into ASAM selects the first tour that corresponds to the solution with minimum total delay (Figure 6).

When there are more than three flight segments affected and considered as part of the solution, the number of combinations increases exponentially given the nature of the traveling salesman problem.
Figure 5: The air traffic control rules allow slot substitutions that can reduce the delay of non-canceled flights. The cancellation of flight 235 leaves an empty slot that can be used by flight 281 and 337 to obtain a revised-controlled arrival time of 16:50. If flight 281 is substituted for flight 235, then its empty slot can be used by flight 337 to obtain a revised-controlled arrival of 17:12. Similarly, if flight 337 is substituted for flight 235, flight 337's revised-controlled arrival becomes 16:50, and flight 281 can use flight 337's empty slot to obtain a revised-controlled arrival of 17:13.

Figure 6: In a network representation of the directed traveling salesman problem, the depot is used to complete the tour of the salesman delivering a commodity (an empty slot for each flight cancellation). The intercity distances in the arcs of the network represent the new delays on the incident nodes (substitute flights). There are two feasible tours in this example out of which ASAS picks the optimal with 67 total delay minutes for the sequence: flight 235 is canceled, flight 281 is substituted for it, and flight 337 is substituted for flight 281.
The heuristic built into ASAM, however, is very efficient and can generate a solution in one or two seconds for large delay programs affecting Chicago O'Hare and Dallas/Fort Worth airports.

Several approaches to solving the traveling salesman problem have been pursued by a large number of researchers [Bellmore and Nemhauser 1974 and Lawler, Lenstra, and Rinnooy Kan 1985]. Some of the most relevant solution methods reported include: minimum spanning trees [Held and Karp 1970], interchange methods [Lin and Kernighan 1973], general optimal solutions [Crowder and Padberg 1980], and ingenious combinations of spanning trees and Hamiltonian circuits to specifically solve the directed traveling salesman problem [Akl 1981]. However, because of the complexity of these problems many heuristic (or approximate) procedures have been developed to find reasonably good feasible solutions that do not require the computational intensity of conventional integer programming procedures.

Heuristic solutions tend to provide fast answers, and they are based on two main approaches: tour building and tour improvement. Examples of tour-building heuristics can be found in Vasquez [1988] and in Mirchandani, Lee, and Vasquez [1988] where the approach is used to solve the concurrent allocation of resources in manufacturing shops. The best example of tour-improvement heuristics comes from an innovative approach outlined by Kirkpatrick, Gelatt, and Vecchi [1982] that takes advantage of similarities between statistical mechanics and discrete optimization to solve the traveling salesman problem using simulated annealing principles.

ASAM uses a tour-building heuristic approach designed to preserve aircraft, crew, and gate connections among flights at hub airports. This heuristic can also handle multiple cancellations for which the problem becomes a multiple directed traveling salesman problem (m-DTSP). An early version of ASAM included a tour-improvement heuristic; but this type of heuristic tends to create conflicts in crew connections and airport gating. Nevertheless, the flexibility of ASAM allows dispatchers to handle substitutions for special flights to improve tours.

**Challenges During Implementation**

The greatest challenge in the implementation was the diversity of computer skills among people responsible for the slot allocation process. I designed the user interface of ASAS to make the automated system easy to understand for the dispatchers with the least computer experience. The system’s flexibility and its use of colored text displays helped users to overcome their initial difficulties, and in a short period of time ASAS became an asset for performing dispatch functions under bad weather conditions.

Another challenge during implementation was getting the dispatchers to accept a micro-computer system application in their environment. The success of ASAS proved to them that such applications have a promising future in real-time airline operations.

ASAS had to be tested and validated in the real-time environment. I ran actual scenarios created by ground-delay programs to get as much feedback as possible from flight dispatchers, who are shift workers and have little time for validation.
of decision-support models. ASAS was completely integrated and tested at the flight dispatch center during approximately three months of continuous user interaction directed toward validation and fine tuning. At the same time, American Airlines started using ASAS for all airports affected, saving over 100,000 minutes of delay during those three months.

**Tangible and Intangible Benefits for American Airlines**

The quantifiable benefits for American Airlines come from two different areas: improved productivity in the dispatch environment, and avoided number of delay minutes at affected airports. ASAS contributed to productivity by reducing the average processing time of ground-delay programs from an average of three man-hours to 10 man-minutes, that is, a 17-fold increase in productivity. At the time ASAS was implemented, system operations control management estimated that a total of eight people per year was needed to make the manual solution process work. ASAS allowed system operations control management to stay within budget by continuing to use one dispatcher for solving ground-delay programs and using new dispatchers for regular flight dispatch functions. The estimated yearly savings for not having to maintain seven more flight dispatchers dedicated primarily to solve ground-delay programs is approximately $455,000 per year.

System operations control management also attributes direct operating cost avoidance to ASAS. The costs avoided are calculated using actual delay cost data collected by the operations engineering department at American Airlines: the flight services department reports cockpit and cabin crew cost data, maintenance operations control reports direct maintenance costs, and each airport reports the cost of fuel consumed on the ground per month. Operations engineering collects these data elements for each subfleet (aircraft type) and develops a weighted average that accounts for the number of flight segments flown by each aircraft type. This average was roughly $15 per minute of delay during 1989. Multiplying that figure by the 345,000 minutes of delay avoided by ASAS results in $5.2 million saved in direct operating costs during 1989 (Figure 7). The maximum savings that could be achieved through a fully staffed manual process covering spoke airports and a small percentage of the flights at major hub airports were estimated at about 35,000 delay minutes (equivalent to $510,000) for 1989, that is, only 10 percent of ASAS actual savings. Currently, the model does not have the capability to measure the down-line effects of delays (that is, the delays imposed on later flights that relate to the flights affected by ground delays because of shared resources: aircraft, crew members, or gates). If it were possible to measure down-line delay effects, it is estimated that the avoided costs would be at least $10.4 million, which represents a 2.12 percent contribution to American Airlines' operating earnings of $490 million for 1989.

The cost for developing ASAS, considering both hardware installation and manpower development, is in the neighborhood of $200,000. Of this only about $50,000 was invested in the development effort. Considering that the productivity improvements of ASAS at system
operations control helped to save $455,000 by avoiding hiring seven more dispatchers, the total tangible benefits of ASAS in one year were $5.655 million, or $18,850 per delay program (there were roughly 300 ground-delay programs in 1989). The costs of development were paid back in less than three ground-delay programs. The total cost of the system was paid back in 11 ground-delay programs.

The intangible benefits of the model include the fact that the expertise for performing arrival slot allocations has become a common asset for flight dispatchers. The dispatch position that uses ASAS is occupied at different times by 20 different dispatchers whose specialized knowledge is enhanced by ASAS’s interactive flexibility and decision support capabilities. This flexibility also means that new personnel occupying the position require very little training.

Dispatchers using ASAS have more time to examine the benefits of reducing delays in different flight segments by performing what-if operating analyses. ASAS what-if analyses capabilities allow flight dispatchers to develop better operating strategies for handling ground-delay programs; for example, they can evaluate the impact of “smart” flight cancellations (not necessarily related to mechanical problems) and their subsequent set of flight substitutions on total delay, before actually performing those cancellations. Smart cancellations provide empty arrival slots and the few passengers inconvenienced are transferred to other flights or compensated by the airline.

Also, the long-term goals in the system operations control business plan have been partially fulfilled; the first microcomputer application in the system operation control
center has been successfully implemented.

**Hidden Benefits and Impacts**

ASAS also contributes to improving American Airlines’ arrival dependability statistics; for several months they have been the highest among major carriers. Arrival dependability is defined by the Department of Transportation as the number of flights arriving within 15 minutes of their scheduled arrival times, divided by the total number of arrivals. Canceled flights are not considered for dependability statistics.

To estimate ASAS impact on dependability, system operations control management took two examples of actual ground-delay programs. The first was a ground delay that affected San Francisco International Airport on January 22, 1989. The delays affected 28 out of the 60 scheduled arrivals. ASAS improved San Francisco’s arrival dependability to 84 percent from a dependability of 40 percent imposed by ground-delay programs. Since American Airlines flew 2,200 flight segments that day, the impact on overall arrival dependability was 1.27 percent. The second example was a ground-delay program affecting 60 arrivals into Chicago O’Hare. In this case, ASAS improved overall arrival dependability by 2.7 percent, from 73.1 percent due to ground-delay programs to 75.8 percent. Further analyses support the conclusion that ASAS improves overall American Airlines arrival dependability by an average 2.2 percent per ground-delay program.

Punctuality has become a powerful marketing tool to build favorable passenger goodwill; but attempting to quantify the benefits of on-time dependability improvements is difficult because of the many variables involved. American Airlines management estimates that every percentage point of dependability increase generates an extra $17 million in revenues (Crandall 1990); customers the airline avoids inconveniencing are likely to make American their primary choice for future travel.

**ASAS improved San Francisco’s arrival dependability to 84 percent.**

The benefits that ASAS has provided to American Airlines can be extended beyond the context of allocation of arrival slots. The modeling and user-interface principles of ASAS can also be used to manage multiple operating resources in real time: aircraft, crews, and airport gates. ASAS modeling concepts are transferable and can provide cost savings, reduced delays, and improved customer service benefits to the entire transportation industry.

**APPENDIX**

**Mathematical Formulation of the Arrival Slot Allocation Model**

The following indices are defined:

- **n** = the number of flight segments in the ground-delay program plus one (an artificial node that represents the depot),
- **i** = the flight segment canceled or replaced, and
- **j** = the flight segment candidate for substitution for a canceled or replaced flight.

The following parameters are assumed to be available to start the slot allocation process:

- **S_i** = the scheduled departure time of flight segment **i**;

---

January–February 1991  59

Copyright © 2001 All Rights Reserved
\(C_i = \) the original-controlled departure time of flight segment \(i\);
\(B_i = \) the flying time of flight segment \(i\) in minutes, calculated as arrival time minus departure time minus taxi-in and taxi-out times;
\(w_i = \) the weighting factor for flight segment \(i\); this gives information about the relative importance of a flight segment with respect to others by considering the number of passengers in each flight;
\(M = \) a large number, such that \(M \geq n\).

The variables are defined as follows:
\(s_i = \) the revised-controlled departure time of flight segment \(i\);
\(x_{ij} = 1\) if the arrival slot of flight segment \(i\) is used by flight segment \(j\), 0 otherwise;
\(y_{ij} = \) a flow variable that delivers one empty slot to each flight segment. There are \((n - 1)\) empty slots at the depot at the beginning. As the substitution sequence is built, one empty slot is allocated to each substitute flight.

The problem is then defined as follows:

\[
\text{minimize} \quad \sum_{i} (s_j - S_j)w_j
\]

subject to

\[
\sum_{i} x_{ij} = 1, \quad \text{for all } i, \quad (1)
\]

\[
\sum_{j} x_{ij} = 1, \quad \text{for all } j, \quad (2)
\]

\[
\sum_{j} y_{ij} - \sum_{j} y_{ji} = -1, \quad \text{for all } i, \quad (3)
\]

\[
y_{ij} \leq Mx_{ij},
\]

\[
C_i + B_i - (s_j + B_j) \leq 20 + M(1 - x_{ij}), \quad \text{for all } i \text{ and } j, \quad (4)
\]

\[
C_i + B_i - (s_j + B_j) \geq -20 + M(x_{ij} - 1), \quad \text{for all } i \text{ and } j, \quad (5)
\]

\(s_i \geq S_j, \quad \text{for all } j, \quad (6)
\]

\(x_{ij} \in \{0, 1\} \quad \text{for all } i \text{ and } j,
\]

\(y_{ij} \geq 0, \quad \text{for all } i \text{ and } j,
\]

\(s_i \geq 0, \quad \text{for all } j.
\]

References


Crandall, R. 1990, Annual president’s conference speech, Dallas/Fort Worth Marriott Hotel, Dallas, Texas.


D. E. Kneram, American Airlines Flight Academy, PO Box 619617, DFW Airport,
Texas 75261-9617 writes "The tangible benefits in direct operating cost amounted
to $5.2 million savings; the manpower requirements for hiring seven more people to
fill the position were very important for my department. Besides, the intangible
benefits were far superior by providing our flight dispatch personnel with the first mi-
cro-computer application in our environ-
ment. ASAS has also helped American
Airlines improve its dependability records
during days when (we) otherwise would
have had to pay a high price to maintain
the integrity of our operations."

January–February 1991  61