Managing daily operations for United Airlines with its size and geographic scope of operations is complex and challenging. Because resources are tightly coupled, even minor perturbations could erode planned operations. United Airlines deploys the System Operations Advisor (SOA), a real-time decision support system at its operations control center (OCC) to increase the effectiveness of its operational decisions. We developed the SOA and implemented it in August 1992. It has been in operation since then. From October 1993 to March 1994, its application saved more than 27,000 minutes of potential delays, which translates to $540,000 savings in delay costs, and the number of flight delays charged to aircraft controllers in systems operations control has dropped by 50 percent since 1992.

United Airlines, one of the major international airlines in the world, operates a fleet of 525 aircraft. The fleet consists of diverse aircraft types, such as B747, B767, B757, B737, and B727 aircraft manufactured by the Boeing Company and DC-10 aircraft manufactured by the McDonnell Douglas Corporation. In 1994, A320 aircraft manufactured by the Airbus Company also joined the fleet. United currently operates over 2,000 flights a day on five continents with major domestic operations in Chicago, Denver, Los Angeles, Miami, San Francisco, and Washington,
DC. Major international operations are concentrated in London, Mexico City, and Tokyo.

Managing daily operations for an airline of United's size and geographic scope is complex and challenging. United uses the System Operations Advisor (SOA), a decision support system at its operations control center (OCC) to increase the effectiveness of its operational decisions.

**Operations Control at United Airlines**

The operations control managers are responsible for meeting departure-completion and customer-service goals in a cost-effective manner. This responsibility is divided between station control centers at the major airports and a centralized operations control center in Chicago. These centers, with real-time access to data on the many facets of operations, make decisions on manpower allocation, cancellations, delays, pilot and flight attendant staffing, as well as flight planning and dispatch to reduce deviation from the schedule and operational plans prepared in advance.

The operations control center ensures that the decisions made are efficient from an overall system perspective. The station control centers (SCCs) work with the OCC to ensure that the decisions at their specific airports are balanced between overall system effectiveness and local performance goals.

Physically, the OCC is a large open room with desks staffed by about 100 controllers, schedulers, routers, and dispatchers divided into five functional groups:

—Meteorology is responsible for forecasting weather events, such as snowstorms and thunderstorms, that have the potential to disrupt flight arrivals and departures.

—Flight dispatch is responsible for planning routes (horizontal track and vertical profile), loads, and fuel, as well as for flight-following tasks and enroute communications with the pilots when necessary.

—Flight crew management is responsible for ensuring that a flight crew is available for each planned departure and for finding a crew if one is not available because of various logistics problems.

—Inflight crew management is responsible for staffing flights originating at spokes with inflight or cabin crew. Unlike the flight crew management group where all staffing is done centrally, inflight crew staffing at hubs is done at hubs.

—System operations control is responsible for overall operation of flights, especially from the aircraft point of view. This group relies on input from other groups and from the maintenance organization to make decisions on delays, cancellations, and routing aircraft for maintenance.

**Aircraft Shortage Problems**

Aircraft shortages are defined as the unavailability of a sufficient number of aircraft to complete all scheduled departures within a specified time window at an airport. Shortages occur for the following reasons:

—A delayed incoming flight causes a temporary shortage until the aircraft arrives.

—A canceled incoming flight causes an extended aircraft shortage usually requiring cancellation of an outgoing flight.

—An aircraft with a mechanical problem causes a shortage until the aircraft is back in service.

Because airlines operate under tight capacity constraints, each delay or cancellation can cause secondary delays or cancel-
lations in the network.

In theory, any shortage problem can be addressed by using spare aircraft. However, keeping enough spare aircraft so that they are available at the right place at the right time is prohibitively expensive. In any case, aircraft shortages need to be managed efficiently, using spare aircraft or otherwise, to keep flight delays and cancellations to a minimum.

**Role of System Operations Control**

Aircraft controllers in systems operations control (SOC) continuously monitor airline operations and manage problems when they occur. Until recently, controllers depended on getting information about the status of the airline from a transaction-processing mainframe. While the mainframe excels at keeping track of data and providing instant information when asked, it is difficult and time-consuming to use when many pieces of contextual information about a problem must be gathered in real time. It is even more complex when multiple aircraft shortages occur simultaneously.

Because of time constraints, controllers operate under stress and, in general, do not have the time to use the mainframe to analyze cost-effective scheduling alternatives. Therefore, they tend to accept delays or cancellations or use spare aircraft, when available, in response to aircraft shortages.

**A Real-Time Decision Support System**

United keeps a reasonable number of spare aircraft available for managing aircraft shortage problems. When feasible, swapping aircraft to reduce deviation from the schedule can also be a cost-effective option. To meet the challenge of finding and evaluating multiple options, we developed and implemented the System Operations Advisor decision support system.

We implemented the system on a network of UNIX workstations to take advantage of the availability of inexpensive computing power and modern graphical user interfaces.

We addressed a number of issues when developing the System Operations Advisor, including the need for:

- A model and algorithm that can operate in a real-time environment;
- A sophisticated interface to communicate with users unfamiliar with technical concepts who had limited time so that they could identify situations appropriate for model use; and
- A data management system that would permit the SOA to obtain large volumes of operational data in real time from the mainframe.

After much research and testing, we developed a minimum cost network flow model (appendix) and adopted a modified version of the Busacker-Gowen algorithm [Busacker and Gowen 1961] as our options for the optimization model component.

To address the issue of quick problem identification and unfamiliarity with technical matter, we developed a graphical user interface (GUI) by working closely with the users and going through manyprototyping iterations. The final result was an interface that isolates the technical details of the model from the user and that solicits input and presents output in everyday operational language.

We solved the real-time data problem by developing an airline database on the UNIX platform that was updated from the mainframes through custom-designed
client-server programs and interfaces. **Subsystems of the System Operations Advisor**

Three components make up the System Operations Advisor:
—The status monitor (SMIT),
—The delay and swap advisor (DSA), and
—The cancellation advisor (CAD).

We implemented the status-monitor and the delay-and-swap-advisor components in 1992. The cancellation advisor is currently in the prototype development stage; we expect to implement it in a production setting in the future.

**The Status Monitor Subsystem**

The purpose of the status monitor (SMIT) subsystem is to alert the operations controller of such problems as delays and cancellations through a graphical user interface. The interface also provides mechanisms to launch such tools as the delay and swap advisor for developing solutions.

The initial menu of the status monitor contains the letters A through T; each letter is a pull-down menu of three-letter airport codes beginning with that letter. When the user chooses an airport, the aircraft-turns window pops out (Figure 1, except the control buttons on the window are not present). Push buttons at the top of the window allow users to launch the appropriate tools. A view of aircraft assignments at the gates can be accessed by pushing the gates button, and on-line help is available through the help button.

Each line in the window shows aircraft turns in real time and includes the status of the flight, such as departed-from-the-gate, off-the-runway, landed-at-the-runway, and arrived-at-the-gate. Each line is

<table>
<thead>
<tr>
<th>FLT</th>
<th>STN</th>
<th>ARR</th>
<th>NOSE</th>
<th>FLT</th>
<th>STN</th>
<th>DEP</th>
<th>DELAY</th>
<th>STAT</th>
</tr>
</thead>
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<td>1300</td>
<td>1235</td>
<td>123</td>
<td>BUF</td>
<td>1345</td>
<td>------</td>
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<td>1200</td>
<td>1236</td>
<td>678</td>
<td>SYR</td>
<td>1346</td>
<td>30</td>
<td>----</td>
</tr>
<tr>
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<td>SEA</td>
<td>1310</td>
<td>7601</td>
<td>289</td>
<td>RIC</td>
<td>1355</td>
<td>------</td>
<td>----</td>
</tr>
</tbody>
</table>

*Figure 1: A screen of the System Operations Advisor shows aircraft turns in real time for monitoring status of scheduled flights. It is also used for setting up the network optimization model for delays and cancellations. Control buttons in the screen are used for opening detailed windows for specifying parameters.*
also a push button that allows controllers to access additional information on the flight, such as passenger counts and the number of connecting passengers. Departures delayed by 30 minutes or more because an aircraft has arrived late or for other reasons, such as unscheduled maintenance, are highlighted in a different color. To summarize, the aircraft-turn window displays a variety of information on the real-time status of the airline at the airport and alerts controllers about deviations from the published schedule.

**Delay and Swap Advisor Subsystem**

Once the controller has identified delays using SMIT, he or she invokes the delay-and-swap-advisor (DSA) using the DSA push button. Next the controller provides inputs that are used to set up the minimum-cost-flow network model (Figure 1). The remove-subfleet and add-subfleet buttons can be used to specify the aircraft types or subfleets within which the controller would allow a swap. The remove-turns button allows the controller to take a particular aircraft out of the model formulation for such reasons as maintenance routing. The do-not-delay button is used to restrict specific departures from being delayed but to allow swapping of the aircraft assigned to this departure. The other-turns button allows the user to view aircraft turns that are not part of the model setup.

When satisfied with the model setup, the controller uses the solve button. At this point, the minimum-cost-flow network model is constructed, and a modified Busacker-Gowen algorithm is applied to derive the solution. The objective function is a weighted criterion of such factors as —Delay passenger minutes, which is a sum of the products of the number of passengers on every flight that are delayed and the actual delay minutes; —Number of passengers connecting to the delayed flights at the current airport; —Passengers connecting at a downline airport arriving on the delayed flights; and —The number of aircraft swaps.

Depending upon the size of the model, within one to five seconds of pushing the solve button, the user obtains the mathematical optimal solution and up to nine other alternative solutions, derived by appropriately perturbing the optimal solution (Figure 2).

The first line of the results summary, solution 0 is the “do nothing” alternative, that is, if aircraft are not swapped to reduce the delay. Each solution line is also a push button, and the controller can click on a solution to examine the details of what is needed to implement the solution. At this point, the controller consults the airport that will actually swap the aircraft and the crew schedulers to check for potential crew conflicts. The controller then orders implementation of the alternative agreed upon by all parties.

**Model Performance and System Usage**

System Operations Advisor was implemented at the Operations Control Center in August 1992. Four aircraft controllers use the system 24 hours a day, seven days a week to track and solve for incoming delays. The delay-and-swap advisor has been used to solve up to 15 incoming delays simultaneously. Computational results recording speed of execution and quality of solutions can be found in Jarrah et al. [1993].

Use of the system from October 1993 to
Figure 2: Summary results presented in this screen contain several alternatives provided by the System Operations Advisor. By clicking on each row, users can examine details of what is needed to implement the corresponding solution.

March 1994 saved more than 27,000 minutes of potential delay. Using a conservative value of $20 per minute of delay, this translates to a $540,000 savings in delay costs in the given period. The more significant statistic is that the number of flight delays charged to aircraft controllers in SOC has dropped by 50 percent since 1992 (Table 1).

**Concluding Remarks**

The impact of the System Operations Advisor has convinced United Airlines management of the need to develop other decision support systems for managing daily operations. The company has implemented a system for identifying and solving flight crew shortages. Systems that help manage gates, passenger flows, and manpower are also under implementation at United's hubs. The airport systems are networked with the systems at the operations control center, thus forming an integrated platform for improved operational decision making throughout United's system.

<table>
<thead>
<tr>
<th>Month</th>
<th>Number of Delays Solved</th>
<th>Delay Minutes Saved</th>
<th>Delay Passenger Minutes Saved</th>
</tr>
</thead>
<tbody>
<tr>
<td>October 1993</td>
<td>37</td>
<td>1,821</td>
<td>317,221</td>
</tr>
<tr>
<td>November 1993</td>
<td>168</td>
<td>6,190</td>
<td>714,006</td>
</tr>
<tr>
<td>December 1993</td>
<td>251</td>
<td>8,495</td>
<td>948,104</td>
</tr>
<tr>
<td>January 1994</td>
<td>127</td>
<td>5,161</td>
<td>573,108</td>
</tr>
<tr>
<td>February 1994</td>
<td>49</td>
<td>1,945</td>
<td>222,706</td>
</tr>
<tr>
<td>March 1994</td>
<td>60</td>
<td>3,900</td>
<td>540,000</td>
</tr>
</tbody>
</table>

Table 1: Application of the System Operations Advisor has resulted in significant savings. This table shows delay minutes savings during a six-month period. It can be observed that more than 27,000 minutes of potential delays were saved during this period, which translates to $540,000 savings in delay costs.
APPENDIX

We provide an overview of the mathematical model in the following. Jarrah et al. [1993] provide detailed formulations.

The network (Figure 3) for solving delay and cancellation problems is built in twodimensional space with airports (stations) represented horizontally and time on the vertical axis. There are four types of nodes:

—Aircraft nodes, labeled “A” and placed on the left at each airport, represent availability of aircraft. Each node is placed at a point of time when it is ready to fly (arrival time from arriving flight plus turnaround time for loading, unloading, refueling, pre-flight check, and so forth).

—Flight nodes, labeled “F” and placed on the right at each airport, represent scheduled departures of flights.

—Spare aircraft nodes, labeled “S” and placed on the right at each airport, represent spare aircraft.

—Aircraft recovery nodes, labeled “R” and placed on the right at each airport, represent availability of “problem” aircraft for re-utilization.

Before defining the arc set, we first categorize the incurred costs due to delays and cancellations. Different arcs will be assigned different costs.

—Type $C_1 = \text{Cost or loss of revenue incurred in canceling each of the scheduled flights.}$

—Type $C_2 = \text{Cost of securing a surplus aircraft for undertaking a flight. This consists of the possible ferrying of the aircraft from another airport and that of bringing it to the departure gate.}$

—Type $C_3 = \text{Cost incurred in swapping aircraft among flights. This reflects the pas-}$

![Figure 3: The delay-and-cancellation problem is modeled as network optimization. Nodes of the network represent arriving and departing aircraft, space aircraft, and recovered aircraft. Arcs of the network represent scheduled flights, connections, and aircraft substitutions.](image)
senger inconvenience involved in changing the departure gates, or, otherwise, the cost for physically moving the affected aircraft to the appropriate gates, informing the flight and maintenance crews of the changes, and so forth.

— Type $C_4 =$ Cost of delaying a flight. This cost accounts for the direct revenue loss, passenger ill will, missing connections at downline stations for connecting passengers, and so forth.

There are four types of directed arcs:

— Scheduled arcs, which connect aircraft to their original assigned flights at the same airport prior to the shortage, that is, from aircraft nodes A to flight nodes F. These arcs are assigned zero costs and aligned from left to right.

— Connection arcs, which connect flight nodes F to aircraft nodes A at the next airport. Note that the next airport is different for different flight nodes. Type $C_1$ costs are assigned to these arcs since the cancellation of the corresponding flights will result in loss of revenue.

— Swap arcs, which connect flight nodes F to aircraft nodes A at the same airport where aircraft swap may be feasible under turnaround time restrictions. These are called backward arcs and are aligned from right to left. Removal of a backward arc is an easy way to exclude a swap if the user desires. This technique can be used to enforce feasibility due to maintenance restrictions, union rules, and reasons of passenger connections. These arcs represent possible swapping of aircraft and are thus assigned costs of type $C_3$ for pure cancellations and assigned costs of both type $C_3$ and $C_4$ for delays.

— Spare arcs, which connect flight nodes F to spare aircraft nodes S or aircraft recovery nodes R, are assigned costs of type $C_2$.

Sources with unit supplies are placed incident to the aircraft nodes where shortages occur. Demands of one or less are placed at the spare aircraft and the aircraft recovery nodes. The inequalities allow the network the choice of using either spare aircraft or the recovered aircraft.

**The Delay Model**

In the pure delay model, as an approximation each station is treated locally. All the connection arcs are removed. The downline effect is reflected in the cost assessment. The network contains disjoint components, each representing a station.

This model solves the problem of aircraft shortages at a station by delaying flights until the shortage aircraft is fixed. It also allows combining delays with usage of spare aircraft available at the station or ferried from other stations. The model is a pure network with arcs bounded by a flow of unity.

One can select what backward arcs to include in the model to effectively enforce the maintenance requirements of the aircraft and duty periods of the flight crews. A backward arc is included in the model only if the aircraft at the head of the arc can take the flight at the tail of the arc and still eventually receive its scheduled maintenance at an appropriately qualified maintenance airport. To check if this condition can be satisfied, the user can search the network of flights exhaustively to see if the aircraft assigned to the flight can reach an appropriate maintenance airport in time.

The model is to be solved as a minimum-cost-flow network. The solution would be a sequence of arcs that starts at a supply node and terminates at a demand node.

If the solution involves an extension in the duty period of a certain crew that fails to accept this extension, then the delay backward arcs for that crew are simply deleted and the model is re-solved so that the duty period for that flight crew will not be extended in the new solution.

**The Cancellation Model**

Figure 3 depicts the network for the cancellation model. The two sets of nodes A and F are necessary to identify which air-
craft is undertaking which flight; this is crucial in this context where changes in the original flight-to-aircraft assignments must be individually checked for feasibility regarding seating capacity and crew-aircraft compatibility and must be kept to a minimum since they imply schedule disruptions, such as possible gate changes for the passengers, informing crews and maintenance personnel of the new schedule, and so forth.

The arcs connecting nodes across stations represent actual transfer across stations of aircraft performing flights. The demand at the spare aircraft nodes and at the recovery nodes is less than or equal to one, thus allowing but not requiring use of these aircraft. Furthermore, an arc would connect a flight to one of these nodes only if it is possible for the corresponding spare aircraft to be made available for the flight without incurring delays. The model is to be solved as a minimum-cost network with flows on all arcs bounded by one. The solution of the network model has flows from sources to sinks representing the canceled flights and new aircraft-flight assignments.

References

John Dansdill, Director, System Operations Control, United Airlines, PO Box 66100, Chicago, Illinois 60666, writes, "In addition to generating tangible benefits claimed in the paper, the System Operations Advisor (SOA) continues to have a dramatic, intangible impact on my employ-ees' ability to find solutions that reduce customer inconveniences during low-volume irregular operations.

"The Status Monitor, by providing alerts on delays and aircraft shortages, has allowed us to respond to problems in a timely manner that was not possible before. Delay and Swap Advisor recommendations which account for aircraft routing and passenger connection issues have also made a real difference. The SOA is playing a critical role in managing the operation of Shuttle by United, our new short-haul operation in the western United States.

"The SOA demonstrates how operations research can be used effectively in the airline operational environment."

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