A New Era for Crew Recovery at Continental Airlines

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Airlines face schedule disruptions daily because of unexpected events, including inclement weather, aircraft mechanical problems, and crew unavailability. These disruptions can cause flight delays and cancellations. As a result, crews may not be in position to service their remaining scheduled flights. Airlines must reassign crews quickly to cover open flights and to return them to their original schedules in a cost-effective manner while honoring all government regulations, contractual obligations, and quality-of-life requirements. CALEB Technologies developed the CrewSolver decision-support system for Continental Airlines to generate globally optimal, or near optimal, crew-recovery solutions. Since its implementation, the system has dealt successfully with several high-profile events, including the December 2000 and March 2001 Nor'easter snowstorms, the June 2001 Houston flood, and most dramatically, the September 11th terrorist attacks. In each case, Continental recovered quickly and obtained overall benefits worth millions of dollars. Continental estimates that in 2001 the CrewSolver system helped it save approximately US $40 million for major disruptions only.
(*Transportation: scheduling, personnel. Decision analysis: systems.*)

On an average day in the United States before September 11, 2001, 15 to 20 percent of commercial airline flights were delayed more than 15 minutes and one to three percent of flights were canceled. The United States Inspector General reported that, during 2000, more than one in four flights (27.5 percent) were delayed, canceled, or diverted, affecting approximately 163 million passengers (United States Inspector General 2001 report). Airlines spend a great deal of time and energy planning and scheduling their operations. They use state-of-the-art processes and automated tools to create plans and schedules that maximize expected revenue and minimize operational

costs. The resulting plans and schedules tightly couple resources, such as aircraft and crew. In general, execution of these plans during normal operations makes the airlines profitable; however, such tight schedules leave the airlines vulnerable to disruptions.

During the day of operations, such disruptions as inclement weather, mechanical problems, the Federal Airline Administration (FAA) air traffic control (ATC) and ground delay program (GDP), and sick crew frequently jeopardize an airline's ability to execute its schedule as planned. Airlines structure their services as networks and design their complex schedules to achieve high resource utilization. As a result, any dis-

ruption has an immediate impact, resulting in flight delays and cancellations, and may also propagate additional disruptions in operations throughout the day and into subsequent days. For example, the skies may be clear and blue with no severe weather anywhere in the United States, and yet a flight may be delayed an hour because a pilot scheduled to fly becomes ill and no replacement pilot is available. With their narrow profit margins, airlines lose money during irregular operations when schedules are disrupted.

In 1994, Continental Airlines, through its primary information-technology provider, Electronic Data Systems (EDS), approached CALEB Technologies' founder, chairman and CEO, Gang Yu, to develop a system for dealing with crew disruptions in real time.

DOT ranked Continental first in on-time performance for the 12 months ending in August 2002.

The goal of the system is to address the problem of recovering crew schedules when disruptions occur. The term *crew* refers to both pilots and flight attendants. In most of our examples, we refer to pilots because their rescheduling is more constrained, but airlines must recover both pilot and flight-attendant schedules to get back to normal operations.

Like a passenger, a crew member may miss a connection when a flight is delayed. Similarly, if a flight is canceled, a crew member may be stranded in an airport, unable to work on a subsequent flight. Pilots are qualified to fly specific aircraft types (for example, Boeing 737, Boeing 747, Boeing 777). Reassigning a flight from one aircraft type to another creates a case in which the originally scheduled pilots—*active crew*—are not qualified to work the flight on the newly assigned aircraft type. The airline must find and assign qualified pilots to cover the flight. We focus on the recovery of active crew back onto their original schedules and the assignment of additional reserve crew to new schedules in response to disruptions that result in crew being unable to fly their assigned flights.

After the "storm of the century" disrupted operations in March 1993, Continental Airlines decided to reengineer its processes for managing its operations and its control center and for recovering from both common and cataclysmic disruptions. Continental contracted with several vendors to design and implement information systems to support its new processes. It also partnered with CALEB Technologies to develop an optimization-based decision-support system to determine the best crew-recovery solutions in real time. With the new processes and systems in place, Continental has become an industry leader in reliability, service, and on-time performance as demonstrated by Department of Transportation (DOT) on-time performance statistics. (The DOT Air Travel Consumer Report ranked Continental first in on-time performance during the 12 months ending in August 2002.)

Continental Airlines Background

Continental Airlines, a major United States air carrier, transports passengers, cargo, and mail. It is the fifth largest United States airline and, together with its wholly owned subsidiaries Continental Express and Continental Micronesia, operates more than 2,000 daily departures to 123 domestic and 93 foreign destinations.

Continental operates its domestic route system primarily through its hubs in the New York metropolitan area at Newark International Airport, in Houston, Texas at George Bush Intercontinental Airport, and in Cleveland, Ohio at Hopkins International Airport. Its hub system allows it to provide passenger services between a large number of destinations more frequently than it would by servicing each route directly. This system also allows Continental to add service to a new destination from a number of cities, using a limited number of aircraft. Each domestic hub is in a large business and population center, ensuring a high volume of passenger traffic. Continental serves more non-US cities than any other US carrier, including cities throughout the Americas, Europe, and Asia. It has more than 50,000 employees, including 4,000 pilots and 8,000 flight attendants.

Continental's system operations control center (SOCC) is located at its headquarters in Houston, Texas. At the SOCC, Continental personnel monitor operations, track the execution of schedules, anticipate

disruptions, and determine the recovery from disruptions. The SOCC provides a central location for making all decisions affecting airline operations, including customer service, crew scheduling, aircraft routing, maintenance scheduling, and dispatch. When disruptions occur, SOCC personnel change the flight schedule, perhaps canceling or delaying flights, route aircraft to support those changes, and finally reassign crew to fly the new schedule. Although they make these decisions sequentially, they do not make them in isolation. They use advanced systems to view the impact one decision may have on another. The operations managers who change the flight schedule and route the aircraft consider the impact on passengers, crew, and required scheduled maintenance in making these decisions. They confer with customer-service representatives, crew coordinators, and maintenance routers when making recovery decisions. After the operations managers determine the new flight schedule and aircraft routings, the crew coordinators take over to assign crew to uncovered flights and recover crew back onto their original schedules.

March 1993: The Storm of the Century and Catalyst for Change

In March of 1993, a super storm hit the east coast of the United States. This blizzard, the worst to hit the United States since the legendary blizzard of 1888, affected 26 states, killed 240 people, and caused approximately $1 billion in damage. The storm dumped over 20 inches of snow in the Southeast, spawned 11 tornadoes in Florida alone, and had hurricane-force winds of over 75 mph. The storm grounded aircraft up and down the eastern seaboard for days. Newark Airport was closed for almost two days.

It took Continental five days to dig out from the storm. Employees located airplanes by brushing the snow off the planes' identification numbers. Crew managers found crews by calling the airports to find out where they had been sent for accommodations. Some crews stayed together and others were dispersed among two or three different hotels. It took days for Continental to figure out where all of its crews were. Most flight crews tried to call in to the operations center but found the phone lines jammed. From an operational standpoint, Continental completely lost control

of its operations. Other airlines were affected as well, but the biggest disruptions were in the New England area and Continental's Newark hub.

Because of the storm, Continental reexamined its operations and processes. The senior management pulled 13 top employees from their duties in the operations center and formed a task force for improving recovery operations. This task force identified inefficient lines of communication and decision-making processes. Continental then rebuilt and reorganized the operations center. It grouped cross-functional decision-making personnel together in the operations

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center. Those responsible for different components of operations, such as aircraft routing, maintenance, crew, and customer service, would now be face to face with each other and jointly make operational decisions in a timely manner. Continental also reorganized crew coordination from a hub-based management system to a fleet-based management system, in which each coordinator would be responsible for an aircraft type rather than a hub. When a disruption occurs at one location, a single person is no longer responsible for recovering all of the affected crew. Instead, four people tackle clearly separable problems.

In 1993, Continental was a conglomeration of systems from a host of different airlines obtained through acquisitions and mergers over the years. Continental had tried to pick the best systems from these airlines but did not always integrate them. For example, it deployed a training-qualification system that operated in isolation from other systems and a flight-control system that did not integrate with the existing crew-management systems for years. After the storm, Continental decided to spend time and resources to determine what it needed to operate its business effectively.

With the help of EDS, Continental toured domestic and international airlines searching for the best-of-breed system that would fit its needs. It was looking for an integrated IT system with real-time decision support in crew management and aircraft routing to

support its new SOCC. It found that most airlines were looking for the same thing.

Continental reluctantly concluded that it would have to build what it wanted. In a monumental effort, it documented its specific requirements for a comprehensive real-time operations database that would share data with all operations applications, the infrastructure required to collect and distribute this data, and the decision-support systems themselves. It awarded EDS the contract for the SOCC database, the supporting infrastructure, and the decision-support systems.

No commercial optimization system for crew recovery existed when Continental began its search. Researchers had begun working on the subject but had reached no consensus on how to recover from operational disruptions and particularly how to recover crew schedules. Outside of the airlines, there was little expertise in the area of airline operations. EDS brought Continental and CALEB Technologies together. CALEB Technologies' founder, Gang Yu, had previously worked with United Airlines to develop an aircraft-routing recovery system (Rakshit et al. 1996). He had also learned about the problems of flight-crew scheduling and recovery from operational disruptions.

Yu and his associates successfully developed a prototype to prove the feasibility of developing such a complex system and to demonstrate the benefits that an optimization-based system could provide in solution time and quality. The prototype was capable of generating solutions in seconds for reasonably sized problems that might take experienced Continental personnel 30 to 40 minutes. The prototype did not contain the complete rules Continental would need to adhere to governmental regulations, contractual obligations, and crew quality-of-life issues, but it did prove its value to an enlightened Continental management that recognized the potential value and efficiency of such a system. Continental executives had the vision to see what this system could do for their airline in dollar savings and in the way they did business—the way they treated their passengers and their crew members.

Continental managers recognized that such a crew-recovery system fit into their corporate go-forward plan. Continental had developed this plan to carry it out of bankruptcy to the top of the airline industry.

The go-forward plan consists of four components: "fund the future, make reliability a reality, fly to win, and working together." The crew-recovery system would fund the future by limiting the impact of operational disruptions on crew, reducing the cost and duration of irregular operations. It would make reliability a reality by producing crew-recovery plans that would minimize the additional flight cancellations and delays due to crew unavailability. With this system, Continental would fly to win by becoming more profitable than its competitors by reducing its operational costs and improving its reliability. This system would support the firm's goal of working together to treat its internal employees and external customers with dignity and respect by providing optimal crew-recovery

Pilots are usually qualified for one position: captain, first officer, or second officer.

solutions constrained by crew quality-of-life requirements that would help the airline to serve its passengers reliably.

Working together, Continental and CALEB Technologies defined the requirements for the crew-recovery system. Continental personnel outlined the characteristics of a good recovery solution and described to CALEB personnel the details, intricacy, and complexity of their business. In their collaboration in defining the goodness of solutions, Continental and CALEB personnel identified two important components for the future system: partial solutions and multiple solutions.

Continental recognized early that, in some situations, the crew available would not be able to cover all the scheduled flights because it had incomplete information about the current disruption or the crew infeasibilities the disruption caused. In this case, Continental wanted to use a buy-time strategy to cover the immediate and most important flights at the expense of leaving later and less important flights without crew. Crew coordinators would then have time to work with the flight-operations managers to modify the flight schedule or to wait until they had more complete information.

We use partial solutions to ensure continuity of operations and to permit decision making when resources are limited. In practice, a recovery solution with some flights uncovered is considered infeasible. However, for real-time decision support, it is not acceptable to determine that the solution is infeasible and give the user no useful information. To carry out operations smoothly with a shortage of resources, airlines must cover as many flights as possible, cover the important flights, and cover the immediate flights so that we can resolve the ensuing problems as more resources become available in the recovery process. By placing a higher penalty on more important and earlier uncovered flights, we can obtain the desired partial solutions.

We came up with the idea of producing multiple solutions after we realized that many scenarios had several solutions that made sense operationally and that some important information would not be available to the recovery system. We realized that (1) because soft costs, such as customer ill will caused by delays and cancellations, would be a factor, experienced users would prefer to examine various high-quality solutions, and (2) often we would not be able to take into account temporary limitations, such as unavailable hotel rooms. With multiple solutions, users have several worthy alternatives and are likely to adopt real-time decision support. They can use their experience and knowledge in evaluating the alternatives before committing to a solution. For instance, an optimal solution to a disruption could require several crews to spend a night in a particular city. This could be problematic if the city is hosting a major convention or event, leaving no hotel space for the crews. A crew coordinator aware of the convention would choose an alternate solution if the system provided multiple solutions to use. The multiple-solution approach relies on crew coordinators to manage the extraordinary situations that cannot be embedded in the optimization model.

Crew Scheduling and the Crew-Recovery Problem

For the major airlines, crew costs constitute the second-largest component of direct operating costs after fuel.

(Yu (1997) discusses a sample of recent research on crew scheduling and crew recovery.) Crew scheduling prior to the day of operations is an important step in using crew resources efficiently. Airlines schedule crews after fleet assignment—assigning fleet types to aircraft routes (markets).

The first of two crew-scheduling problems is the crew-pairing problem. A crew pairing is a sequence of flight legs beginning and ending at a crew base that satisfies all governmental and contractual restrictions (also called legalities). A crew base is a city where crew pairings start and end, not necessarily where crew members live. Continental's crew bases include Cleveland (CLE), Houston (IAH), and Newark (EWR). Crew pairings generally cover a period of one to four days. The crew-pairing problem is to find a set of pairings that cover all flight segments at minimum cost. Analysts have generally modeled it as a set-partitioning problem in which pairings are enumerated or generated dynamically (Graves et al. 1993, Hoffman and Padberg 1993, Stojkovic et al. 1998). Others attempting

> The combinational nature of the problem easily leads to millions of possible alternatives.

to solve this problem have employed a decomposition approach based on graph partitioning (Ball and Roberts 1985) and a linear-programming relaxation of a set-covering problem (Lavoie et al. 1988). Often airlines use deadheading, the practice of moving crews on flights as passengers, to reposition flight crews. Thus for the crew-pairing problem, the airline must cover all flight segments but may cover them with more than one crew. Indeed, solving the crew-pairing problem is recognized as a critical function within the airlines, and the researchers who advanced the state of the art, such as Edelman finalists Anbil et al. (1991), have recognized this as well.

The second of the related crew-scheduling problems is the problem of generating monthly bid lines, sequences of pairings, to which crews are assigned for a month. Bid lines are also subject to legalities. Airlines construct bid lines to satisfy a number of objectives, including workload balancing and crew quality of life.

In balancing workloads, airlines try to minimize the variance of hours of flight time (block hours) among the bid lines created for a crew base. They address quality-of-life considerations in the composition of one-, two-, three-, and four-day pairings in the bid line. One crew member may prefer a bid line composed of a repeated pattern of one four-day pairing followed by three days off while another may prefer a bid line consisting of one-day and two-day pairings.

Airlines generally construct bid lines and assign them to their crews through seniority-based bidding processes, or they use preferential bidding systems to create personalized bid lines for specific crew members that take into consideration their crew member's indicated preferences and such activities as training sessions and vacations (Gamache et al. 1998, Nicoletti 1975).

To cover different markets and to meet various demands, most major carriers operate several aircraft types, such as Boeing 737, McDonnell-Douglass 80, and DC 9. Pilots are usually qualified to fly only one type, but flight attendants can generally serve on all types. Also, pilots are usually qualified for one position: captain, first officer, or second officer. Pilots must also have specific qualifications to serve on certain international routes and land at specific airports. Similarly, airlines create some pairings for flight attendants who speak particular languages for international flights. These qualification limitations, along with governmental and contractual legality rules, restrict crew assignments and reassignments.

On the day of operations, decisions to add, cancel, delay, and divert flights and to reassign flights from one equipment type to another create situations in which crews cannot serve the flights in their pairings, leaving flights without crews. These decisions serve as inputs to the crew-recovery system. Operations managers cancel, delay, divert, add, or reassign flights in their attempts to return the airline to normal operations. They must weigh such factors as reaccommodating passengers, impacts on crews, and aircraft-maintenance requirements when modifying flight schedules for a feasible and desirable recovery plan.

In addition to coping with operational disruptions, managers must identify replacements for crew members who cannot work because of illness or some emergency in the middle of an assigned pairing or who fail to connect with an assigned flight because a prior flight is delayed to the point that the crew is unable to connect to the next flight in his or her pairing. Occasionally, crew members cannot serve flights because they would violate a legality rule, such as a duty-hour limit.

The goal of the crew-recovery system is to minimize the incremental costs for qualified crew to cover the remaining flights in the schedule while retaining the assigned pairings as much as possible. Covering all of the flights limits further disruption to the flight schedule. Also, returning crew members to their assigned pairings and limiting the number of crew members unaffected by the disruption who are reassigned preserve the value and quality of life built into the original pairings. Speedy solutions also limit the extent of disruptions. By producing desirable recovery solutions quickly, airlines can avoid additional delays and cancellations, improve on-time performance, reduce the number of passengers to reaccommodate, and preserve passenger goodwill.

The Architecture of the CrewSolver System

The improvements we made to the SOCC decision-making processes and databases helped crew coordinators to fully understand the impact of operational disruptions. However, without a decision-support system for recovery, they would have had to produce recovery solutions manually, which process could take hours for even moderate disruptions because of the complexity of governmental and contractual legality rules and crew quality-of-life issues. The combinatorial nature of the problem easily leads to millions of possible alternatives.

Working closely with Continental crew coordinators, CALEB personnel defined, designed, and implemented an optimization engine that incorporates the logic to produce feasible solutions that satisfy legality requirements and promote crew quality of life. CALEB also worked closely with EDS to design and implement a system to be deployed in the infrastructure EDS developed. The resulting application is a complete, reliable, constantly available, real-time decision-support system called CrewSolver, which supports availability 24 hours per day, seven days per week (Figure 1).
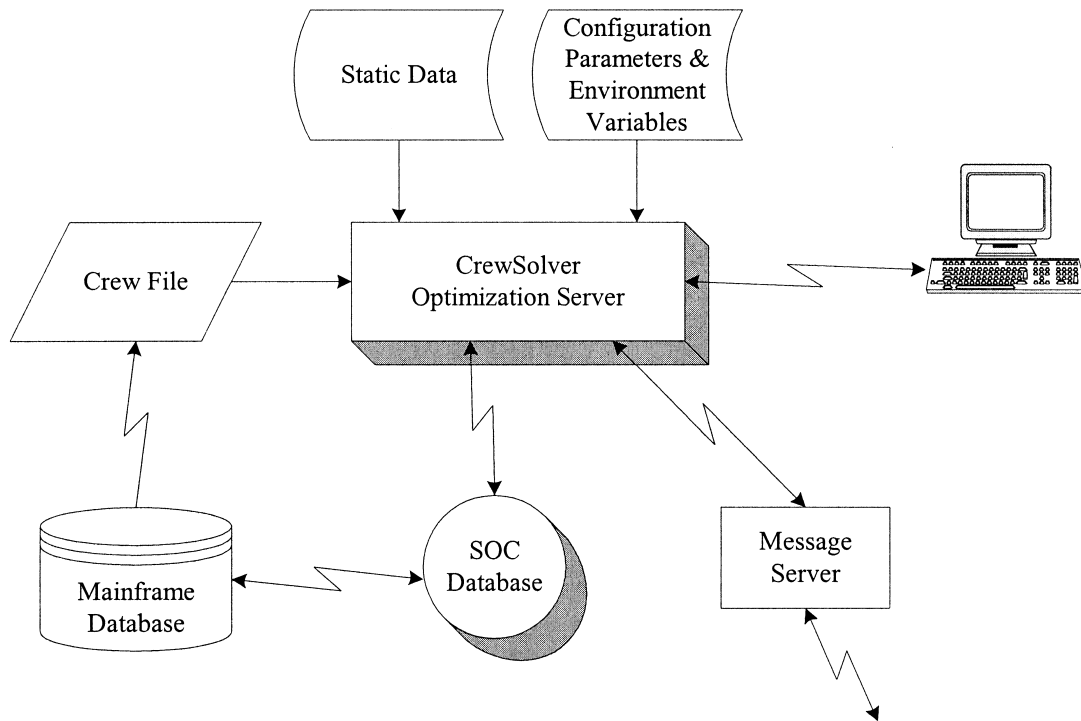
Figure 1: The CrewSolver system architecture consists of an optimization server with interfaces to various data sources and a connection to crew clients—the graphical user interface crew managers use to view disruptions and access the optimization server. Upon initialization, the optimization server retrieves static data from electronic files and live operational data from the system operations control (SOC) database. After initialization, the optimization server receives update messages regarding modifications to the current state of operations. The optimization server uses an in-memory data store that represents the operational status and has an embedded legality checker and algorithms that solve the crew-recovery problem and give the user multiple solutions.

For performance reasons, the CrewSolver optimization server contains an in-memory data store representing current operations. The system initializes the data store with live operational data from the system operations control (SOC) database, crew data retrieved from mainframe systems, static data maintained in electronic data files, and optimization parameters also maintained in electronic data files. The system updates the data using messages from a message server.

A crew coordinator uses a graphical user interface to request the optimization server to provide a recovery solution. The optimization server sets up a problem scenario based on the data the user inputs and the in-memory data store. The solver then generates up to three solutions (Figure 2). Solutions consist of
—Reassigning crews from one flight to another,

—Deadheading crews to cover a flight or return back to base,
—Holding crews at their current locations,
—Assigning crews additional duty periods,
—Moving a crew's layover to a different city, and
—Using reserve crews to cover flights left uncovered by active crews.

When flights are canceled, for example, two linked flights, a flight from Newark, NJ (EWR) to Raleigh-Durham, NC (RDU), and a flight from RDU to EW, the two cockpit crews, each consisting of a captain (CA) and a first officer (FO), will not be in place to fly their scheduled flights immediately following the canceled flights. One solution would be for one crew to end its duty with its previous flight, for the second crew to work a flight left open by the first crew and then return

Original Pairings

Pairing: PE5250

1434/PHX:0740-EWR:1414	445/EWR:1710-RDU:1856	344/RDU:1930-EWR:2100
	cancelled	

Pairing: PH5370

1550/IAH:1040-RDU:1413	56/RDU:1625-EWR:1802	567/EWR:1940-PVD:2045	1573/PVD:1325-EWR:1430	1281/EWR:1610-SEA:1905	...
	cancelled				

Modified Pairings

Pairing: PE5250

1434/PHX:0740-EWR:1414

Pairing: PH5370

1550/IAH:1040-RDU:1413	344/RDU:1930-EWR:2100	1281/EWR:1610-SEA:1905	...

Pairing: PE5X01

567/EWR:1940-PVD:2045	1573/PVD:1325-EWR:1430

Figure 2: CrewSolver generates this solution in response to the cancellation of flight 445 from Newark, NJ (EWR) to Raleigh-Durham, NC (RDU) and flight 56 from RDU to EWR. The solution shows the following: the crew assigned to pairing PE5250 completes its pairing with flight 1434, and the crew assigned to pairing PH5370 will take flight 344 from RDU to EWR, which was left open by PE5250, and then return to its assigned pairing on flight 1281 from EWR to Seattle, WA (SEA). The two flights left open by PH5370, flight 567 from EWR to Providence, RI (PVD) and flight 1573 from PVD to EWR, form a pairing that will be assigned to a reserve crew.

to its assigned pairing, and for a reserve crew to fly the two flights left open by the second crew (Figure 2).

The user obtains the solutions generated through the graphical user interface.

Integration at Continental Airlines

The CrewSolver system is but one of several crew-related systems at Continental. It is integrated with the system operations control center (SOCC) database, the crew-management system (CMS), and the crew-operations-management system (COMS) graphical user interface to provide the day-of-operations crew system (Figure 3). The day-of-operations crew system and the day-of-operations flight system exchange updates the crew and flight schedules.

The day-of-operations crew system sends crew revised information on schedule changes via the Internet and the company intranet. Pilots and flight attendants then review their schedules and reply to the system to acknowledge schedule changes.

The day-of-operations crew system uses flight schedules generated by the flight-scheduling system and the schedule-synchronization system and pairings generated by the crew-pairing optimization system to determine what the airline plans to fly over a particular period of time and how it will make the transition to that plan and adapt to deviations from it. It uses the manpower-planning system with the flight-scheduling system to generate plans for hiring and training pilots and flight attendants and for staffing the scheduled flights. Thus the day-of-operations crew system is the beneficiary of data produced by the planning and scheduling systems as much as a year before the day of operations.

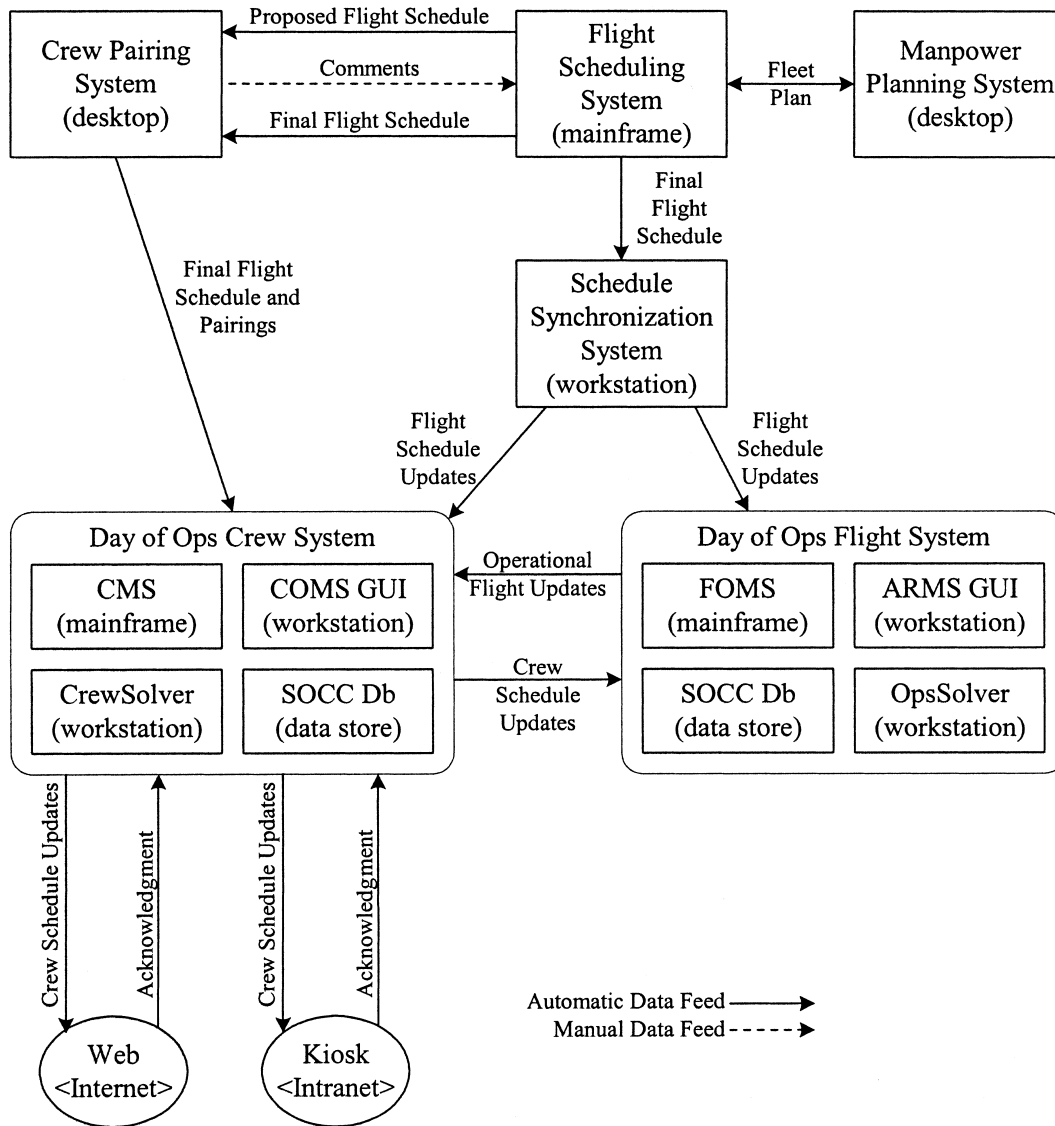On the day of operations, Continental crew coordi-

Figure 3: Continental's crew-related systems are connected. CrewSolver is directly connected to the crew-management system (CMS), the crew-operations-management system (COMS) (which serves as the interface for the CrewSolver system), and the system-operations-control-center (SOCC) database. It is indirectly connected to the crew-pairing system, the schedule-synchronization system, and the day-of-operations flight system, which includes the flight-operations-management system (FOMS) and the aircraft-routing management system (ARMS). It also uses output produced by the manpower-planning system and flight-scheduling system.

nators use the day-of-operations crew system to monitor ongoing crew activities, detect operational disruptions, and resolve crew disruptions. In resolving crew disruptions, the coordinators use the CrewSolver system whenever a crew-recovery solution is not immediately obvious (about 36 times in the first quarter of 2002).

Continental assigns its crew coordinators to specific fleets, and they use CrewSolver to resolve minor crew disruptions within those fleets. A crew coordination

manager uses CrewSolver to resolve larger crew disruptions that concern multiple fleets and major disruptions involving all fleets.

In anticipation of predicted operational disruptions, due to weather, for example, flight operations managers use a flight operations recovery system called the OpsSolver system (developed by CALEB) to propose schedule modifications. They pass these modifications in data files to the CrewSolver system to determine the corresponding crew-recovery solution. Working together, the flight operations managers, crew coordinators, and crew-coordination managers review the alternative solutions and choose the one that best recovers the airline's operations.

The system routes the chosen solution to the crew-management system (CMS) for implementation. CMS owns the crew data and schedules. Similarly, the system routes the flight-operations-recovery solution to the flight-operations-management system (FOMS) for implementation.

Impact at Continental Airlines

Continental Airlines estimates that it saved approximately $40 million during 2001 as a direct result of using the CrewSolver system to recover from four major disruptions only. For the first quarter of 2002, Continental estimates that it saved approximately $5 million by using the CrewSolver system to recover from minor disruptions. These savings include fewer enroute and predeparture delays, fewer minutes per delay, fewer cancellations, reductions in ferry flights and diversions, fuel savings, crew-penalty savings, and hotel and per diem savings. In addition, Continental recognized improved on-time performance, reductions in reaccommodating passengers, and improved passenger goodwill. The CrewSolver system also provided faster and more efficient recovery solutions than Continental's previous system and higher quality of life for crews. Continental claims that, without the Crew-Solver system, it could not have recovered from the disruptions and schedule changes resulting from the September 11, 2001 terrorist attacks, which halted all flights for several days and drastically reduced demand for flights.

In 2001, Continental Airlines faced several major disruptions with very different characteristics. In each case, Continental used the CrewSolver system to get back on schedule in record time. These disruptions included a major snowstorm on New Year's Eve weekend, another snowstorm in March, a devastating flood in June, and the devastating terrorist attacks of September 11, 2001.

On Friday, December 29, 2000, a major snowstorm began moving into the New York area. That day, Continental operations managers precanceled 35 percent of their flights at Newark for Saturday. It took Continental personnel over three hours to determine the revised flight schedule and aircraft routings; the result was 112 flights canceled for Saturday. The crew solution for the 737 fleet, the largest aircraft fleet at Continental, affected 144 pairings. The CrewSolver system generated a solution for the cancellations in 3.5 minutes. Without the CrewSolver system, crew recovery at Continental was the bottleneck in the process of generating a complete recovery plan for the airline. With CrewSolver in place, the bottleneck has been pushed up to the flight- and aircraft-recovery process.

Continental used the CrewSolver system again on Saturday as the storm worsened and completely shut down the Newark hub. Other major airlines took as many as three days to recover, with follow-on cancellations and delays into Tuesday. Continental was back on schedule and running normal operations by noon on Sunday. Crews made no complaints about their rerouted solutions, and Continental noted using fewer crew reserves than it had in similar past disruptions that it had solved manually (although data supporting this last claim is unavailable).

Continental estimates that it saved approximately $4,422,000 by using CrewSolver for this disruption. These savings came primarily from avoidance of flight cancellations due to crew unavailability and reduced crew costs. It also realized additional revenue by accommodating other airlines' stranded passengers.

Another Nor'easter descended upon Newark on March 4, 2001. This storm was predicted to be the next great "storm of the century." At noon on Sunday, Continental decided to cancel 141 flights in and out of Newark for Monday. In the past, the crew coordinators

would have had to start working on a solution immediately, but because CrewSolver had worked so successfully during past disruptions, the head of crew coordination waited until evening to begin generating a crew solution. By then the airline had better information about the storm.

At 7:00 pm, Continental used CrewSolver to generate solutions for its 757, MD 80, and 737 crews. It encountered an unexpected problem. The solutions were so extensive that printing them out on a dot-matrix printer for crew notification took four hours. Continental realized that its million-dollar optimization system needed supporting infrastructure, and it bought a new laser printer for the operations center. Even with the printer difficulties, Continental had notified all the crews of their schedule changes by Monday morning, and it handled the additional weather disruptions on Monday and Tuesday quite easily with additional solutions from CrewSolver.

Continental estimates that it saved approximately $1,119,000 by using the CrewSolver system for this disruption. The savings come mostly from avoiding flight cancellations due to crew unavailability. The ability to wait until it had more accurate weather data also permitted Continental to avoid unnecessary cancellations.

Continental used the CrewSolver system again in June 2001 when Houston Intercontinental Airport (IAH) closed for a day after a devastating flood brought on by heavy rains from Tropical Storm Allison. Continental set a record for the number of diverted aircraft in one day as no aircraft were able to land at IAH and Houston Hobby (HOU) airports. In addition, most Continental operations personnel could not get to work because many major freeways were closed—and those on duty could not get home. The center operated throughout this disruption with a skeleton crew, made up mainly of people who were on duty over 24-hours. Continental estimates that it would have taken the crew coordinators 72 hours to solve the problems manually, but with the CrewSolver system, they solved the problem and notified all of the affected crews in eight hours.

Continental estimates that the CrewSolver system saved $5,425,000 for this disruption. Again, the primary savings came from avoiding additional flight cancellations due to unavailable crews. In this case, Continental basically shifted its operations out of Houston to its other hubs and used the crews that were available to fly the remainder of its flights. Although the storm closed the Houston airports, Continental used CrewSolver to limit its impact on the rest of its operations.

The most important test of the CrewSolver system's abilities came on and after Tuesday, September 11, 2001, when the FAA closed the airspace over the United States and diverted all planes to the nearest airport following the attacks by terrorists using four aircraft from major US carriers. As a result, Continental canceled all scheduled operations through Friday morning. Throughout the week, Continental used the CrewSolver system, along with the OpsSolver system for recovering flight schedules and rerouting aircraft, to determine the best method of resuming operations when the FAA reopened the airspace. It used OpsSolver to determine the best set of flight cancellations, delays, additions, and aircraft routings. Solutions from the OpsSolver system were passed into the CrewSolver system for comprehensive recovery solutions.

The first 737 crew solutions the optimization system returned rerouted approximately 1,600 pairings; the problem included more cancellations and a larger time window (four days) than any Continental or CALEB had ever imagined. The system solved this problem in less than 17 minutes. CALEB and EDS personnel were available to Continental throughout to make any changes needed.

One notable change we made to the optimization server was to extend the problem window to as much as two weeks. After September 11, Continental and other major airlines reduced their flight schedules by 20 percent for the remainder of September. After working for an hour on the disruptions to the crew schedule caused by this 20 percent reduction and realizing the monumental task it faced, Continental asked CALEB personnel if they could extend the optimization server to solve problems for the rest of the month. The CrewSolver system was designed to load seven days of data—the current day, plus three days in the past and three days in the future—for the purpose of checking legality. The new scenario called for loading over 14 days of data and solving a time window of 10 days.

CALEB, Continental, and EDS personnel together solved the data issues for the expanded window, and CALEB modified the optimization system for Continental.

CrewSolver gave Continental an advantage over other US airlines following the attacks on September 11 (Figure 4). Continental used CrewSolver in determining a new operational schedule for the rest of September. It produced a schedule it could execute reliably (Figure 5). Continental planned almost all of its flight cancellations before the day of operations. On the day of operations, it was able to execute those plans successfully.

Because of its successful planning, Continental delayed fewer flights than the other airlines. Because it knew how to recover its crew, it suffered fewer delays caused by crew unavailability. Because it could generate a plan and use CrewSolver to recover its crew, Continental could publicize its schedule changes and reaccommodate affected passengers. Continental offered its passengers a consistent and more reliable schedule than most of the other airlines.

For the month of September, the CrewSolver system generated solutions modifying 5,866 pairings involving 11,921 crew members. Not a single pairing in the system for the remainder of September was unaffected by the schedule reduction. Continental's completion factor (ratio of completed, noncanceled flights to scheduled flights) for the month of September was 81.2 percent. Excluding cancellations due to the terrorist attacks and the subsequent schedule reduction, its completion factor was 99.7 percent. Since then, Continental has set company and industry records with eight 100-percent-completion days in October 2001, nine in January 2002, and 14 in February 2002, along with an all-time-company-record completion factor of 99.9 percent for February 2002. To sum it all up, Continental claims that without the CrewSolver system it could not have recovered from the disruptions and schedule changes caused by the September 11, 2001 terrorist attacks.

Continental estimates that it saved $29,289,000 by using CrewSolver to recover after the September 11 disruption. More than half of the savings ($15,051,000) came from avoiding flight cancellations due to crew unavailability. Most of the rest came from avoiding added crew costs ($6,007,000) and avoiding losses of future revenue from passengers that would have been on unnecessarily canceled or delayed flights ($6,660,000), respectively. The remainder of the savings came from avoiding unnecessary flight delays due
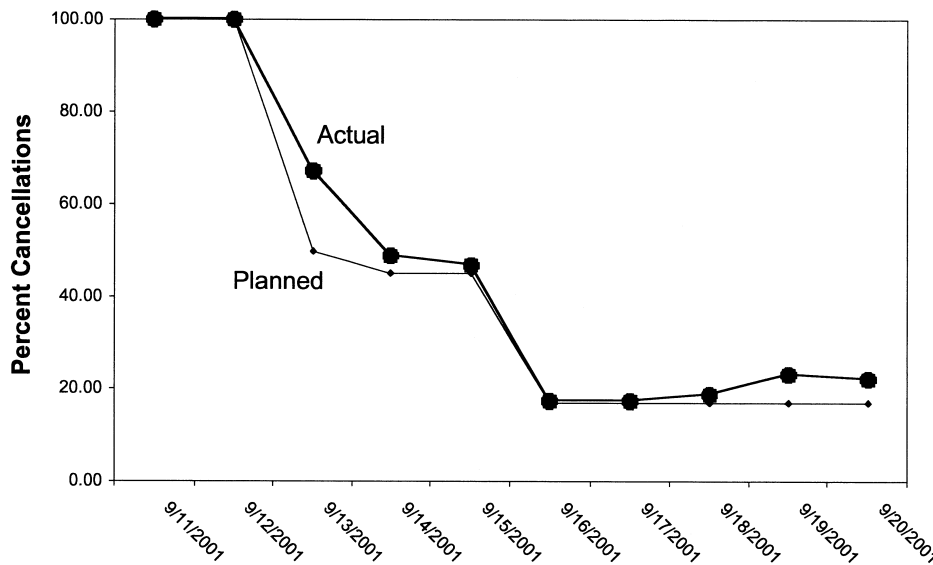

Figure 4: While other airlines canceled many more flights than they had planned to cancel in the days following September 11, 2001, Continental's cancellations followed its plan.
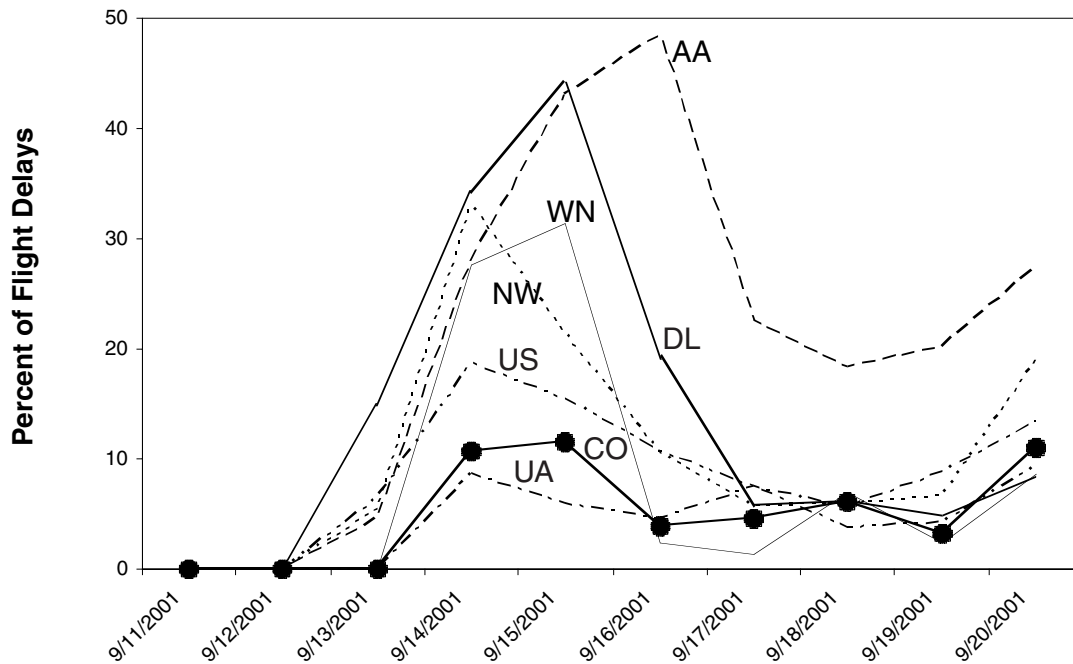
Figure 5: Because Continental used CrewSolver to replan its operations, it executed its new schedule more successfully and with fewer delays than most of its US-based competitors. The abbreviations in the chart are the following: American Airlines (AA), Continental Airlines (CO), Delta Air Lines (DL), Northwest Airlines (NW), Southwest Airlines (WN), United Airlines (UA), and US Airways (US).

to crew unavailability ($1,175,000) and avoiding overtime pay to reservations and airport-services personnel ($396,000), respectively.

Contributing to the costs of flight cancellations are crew pay and station costs. We assumed that the airline incurs these costs when a flight is canceled with no benefit in return. Additional liabilities for crew pay include contractual pay for rescheduled flights, pay for excess duty, pay for extended duty, pay for days originally scheduled off, pay for guaranteed minimum flight time for all crew members, and additional, unexpected hotel and per diem costs. We determined lost future revenue through historical analysis, observing that 10 percent of passengers on canceled flights do not return to Continental and three percent of passengers on delayed flights do not return to Continental. Costs for delayed flights include additional crew pay, fuel, maintenance, and airport costs. Thus pay for unutilized crew and liabilities for additional crew pay are key contributors to the airline's cost for crew recovery

during irregular operations. By limiting the impact of the irregular operations on Continental's crews, CrewSolver helps the airline to use its available crews and avoid unnecessary crew costs.

Successes, such as the CrewSolver system, show that Continental is a trailblazer in adopting technology. The CrewSolver system has been very helpful to Continental Airlines:

—Most airlines make money during regular operations but lose money during irregular operations. The CrewSolver system addresses the bottleneck in recovering from operational disruptions, recovering crews.

—The CrewSolver system is available 24×7.

—The CrewSolver system has saved Continental Airlines more money than any other single application: $40 million savings for four major disruptions in 2001 (versus net revenue of $341 million in 2000 and a net loss of $95 million in 2001).

—It has saved the airline an estimated $5 million for daily disruptions in the first quarter of 2002.

—It has saved Continental $1 to $5 million for every major disruption.

—Speed is money. CrewSolver has cut the time it takes Continental to recover, reducing the cost and lost revenue from irregular operations.

—CrewSolver promotes what-if analysis, allowing the airline to easily and quickly examine different scenarios before making decisions that concern large sums of money.

—Continental Airlines now reacts to facts, not forecasts. The system's speed allows operations personnel to wait for accurate and complete data before making decisions.

—Reduced recovery time reduces the impact of disruptions on the flying public.

Conclusions

Continental Airlines is committed to adopting technology to improve its operations. Among the major US airlines, Continental is early in using decision-support tools to recover from day-of-operations disruptions. In doing so, it has reaped the rewards of consistent and reliable operation. It is considered one of the best airlines in the industry with respect to on-time performance and customer satisfaction (DOT Air Travel Consumer Report 2002).

With the addition of the OpsSolver system, Continental now has the tools to produce comprehensive recovery solutions for both aircraft and crews. Together, OpsSolver and CrewSolver generate recovery solutions that retain revenue and promote customer satisfaction at little cost. The CrewSolver provides crew-recovery solutions that support the disrupted flight schedule at the lowest cost possible while maintaining a high quality of life for its pilots and flight attendants.

Other airlines are aware of Continental's success and have contracted with CALEB to license its decision-support systems for operations recovery. Southwest Airlines began using its customized implementation of the CrewSolver system in the summer of 2002. Its

crew-management personnel use the CrewSolver system several times per day every day. Northwest Airlines expects to have its customized implementation of the CrewSolver system in production by the end of 2002.

Continental and CALEB have forged a successful partnership dedicated to solving real problems that affect millions of people every year. Continental is a pioneer in determining the way an airline should manage its operations. CALEB is also a pioneer in applying operations research to support Continental's vision and to solve real operational problems.

Executive summaries of Edelman award papers are presented here. The complete article was published in the INFORMS journal Interfaces [2003, 33:1, 5-22]. Full text is available by subscription at http://www.extenza-eps.com/extenza/contentviewing/viewJournal.do?journalId=5