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DISCRETE EVENT SIMULATION MODEL FOR AIRLINE OPERATIONS: SIMAIR

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ABSTRACT

SIMAIR is a C++ based research tool meant for the simulation of airline operations. It provides a means for devising and evaluating various airline recovery mechanisms to handle disruptions, and can also be used as a tool to evaluate the performance of a given schedule of operations. The performance of a given recovery mechanism can be quantified for research and evaluation purposes.

1 INTRODUCTION

Day-to-day airline operations encounter various kinds of unexpected disruptions. Unexpected aircraft delays, maintenance problems of aircraft, crew unavailability and severe weather conditions at airports that prohibit aircraft from taking off and landing, are among the different sources of disruption to the smooth operation of an airline schedule. These disruptions to the schedule also translate into loss of passenger revenue, and loss of passenger goodwill as well as sub-optimal crew utility.

Unfortunately, a typical preplanned airline schedule does not take these disruptions into consideration, and is packed to the fullest. As a result it is usually not very robust and does not accommodate well the many unexpected disruptions during operations.

In the event of a disruption, airlines employ various recovery procedures in an attempt to bring the operation back to its original schedule as soon as possible. Hence, how well an airline copes in the face of disruptions also largely depends on the recovery procedures of that airline. A typical recovery procedure considers alternatives such as cancellation of flights, re-scheduling of flights or aircraft swapping. The efficiency of the recovery procedure thus directly influences the performance of the schedule, which in turn influences the revenue of the airline.

Researchers (Teodorvic 1984, Teodorvic 1990, Rosenberger et al. 2001, Lettovsky 2002, Wei 1997) have studied the effect of recovery procedures in the event of a schedule disruption. The focus of these studies has been mainly on aircraft recovery (Teodorovic and Gubernic 1984, Teodorvic and Stojkovic 1990, Jarrah et al. 1993, Yan and Young 1996) and crew recovery (Lettovsky 2002, Wei 1997, Lettovsky 1997). There has been some work in the area of integrated recovery (Lettovsky 1997) where all of the above-mentioned recovery procedures were accounted for in one model of operations.

Teodorvic and Gubernic (1984) dealt with schedule perturbation caused by aircraft unavailability. They attempted to find a new daily airline schedule whenever an aircraft becomes unavailable. Teodorvic and Stojkovic (1990) extended this work by proposing an integer-programming model, which minimizes the number of cancelled flights while considering airport closing time. Jarrah et al. (1993) provided a network flow model to minimize the cost incurred due to aircraft shortages. Yan and Young (1996) were the first to attempt to provide a model that accounts for aircraft delay and cancellations simultaneously. Arguello et al. (1997) considered the problem of airline schedule recovery in the event an aircraft becomes temporarily unavailable. Rosenberger et al. developed a model that reschedules legs and reroutes aircraft. A heuristic for which aircraft to be rerouted was also provided.

Teodorovic and Stojkovic (1990) were the first to consider crew planning. They considered the schedule disturbance caused by absence of aircraft, unavailability of crew or change in leg departure time. The legality in crew rotations was also considered. Lettovsky et al. (2002) considered the problem of reassigning crews to restore a disrupted crew schedule. Wei and Yu (1997) proposed an integer network flow model and a heuristic search algorithm for a system-recovering process due to complicated crew schedules and restrictive crew legalities within the scope of a hub-and-spoke model.

Lettovsky (1997) formulated and discussed an integrated recovery model for optimal recovery consisting of crew, aircraft and passengers. This formulation consists of large and computationally intractable mixed integer linear programming problems. This is then divided into smaller sub-problems to facilitate the problem solution.

Unfortunately, without a common framework, it is difficult to conduct a performance comparison between these different recovery algorithms.

The objective of our research effort is twofold: to evaluate the robustness of a pre-planned airline schedule in the event of operational disruptions, and to act as a common framework upon which different recovery policies can be run and compared. To achieve the above stated objectives, we propose a discrete-event simulation model named SIMAIR for **SIM**ulation of **AIR**line operations. SIMAIR simulates airline operations by taking into consideration various aspects of aircraft, crews, airports, delays and weather conditions.

Discrete-event simulation (Rizzoli 2002, Takahashi 2002) has been used to model rail and road transportation problems. Rosenberger et al. (2000) developed a stochastic model for airline operations and have set the motivation for SIMAIR. The model that was developed in Rosenberger et al. (2000) was not modular and did not allow other recovery procedures to be integrated. In this paper we propose a modular method of approaching the problem that can deal with different recovery procedures from different researchers or airlines. Hence, this work is an extension of model developed by Rosenberger et al. (2000) at the Georgia Institute of Technology.

2 APPLICABILITY OF SIMAIR IN RESEARCH

SIMAIR is a research tool used to simulate daily operations of airlines. As mentioned in the previous section, the purpose of SIMAIR is twofold.

Researchers can use SIMAIR to evaluate the robustness of their flight schedule in the face of unexpected disruptions. One can use historical data to provide a series of scenarios of disruptions, and using existing recovery policies, one can see how well the flight schedule performs at the end of a simulation run.

Researchers can also use SIMAIR as an evaluation tool to evaluate the effectiveness of their recovery policies. There have been numerous attempts over the past years to provide effective recovery policies in the face of disruptions. However, lacking a common tool, it is difficult, and sometimes impossible, to conclude which recovery policy outperforms the other. SIMAIR can be used as a common tool to allow comparison studies between these different recovery policies.

Most airlines currently employ humans to perform recovery in the face of a disruption, rather than using optimization algorithms for this task. SIMAIR may also be used as a training tool for airline employees to come up with recovery decisions under simulated conditions.

3 SIMAIR MODEL DESCRIPTION

SIMAIR is written in C++ code in an object oriented approach. SIMAIR consists of three main modules namely simulation, controller and recovery. The organization of the conceptual modules is shown in Figure 1.

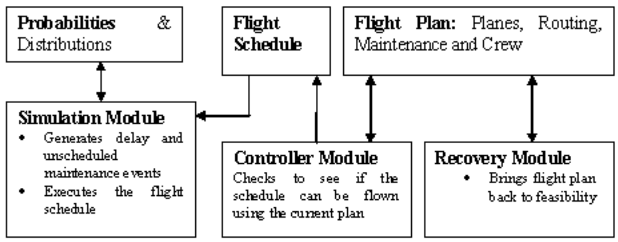

Figure 1: Modular Structure of SIMAIR

The flight schedule is made up of legs that the airline will fly with its fleet and crew. The schedule is read into the simulation module in a pre-defined format. SIMAIR then simulates the operation using the schedule provided.

The simulation duration of airline operations in SIMAIR is dependent on the input schedule provided. The user can also run the simulation over many iterations, to obtain aggregate results.

The simulation module is solely involved in simulating operations. It is made up of a few components, such as a future event list, an event scheduler, and a simulation clock.

The controller module plays the role of schedule legality checker. The controller is called at different stages of the simulation to check for schedule legality and calls the recovery module in the event of a disruption that causes illegality. After the recovery module comes up with an alternate plan, the controller module will first check for legality of the proposed plan, and then implement the changes recommended if the proposed alternative is legal.

When there is a disruption in the operations, the recovery module is called to come up with actions to bring the schedule back to normal. The recovery module houses the different methods or policies that airlines use to deal with disruptions or irregularities.

The stochastic aspects of the simulation like gate delays, and unscheduled maintenance are handled using a probability distribution.

SIMAIR is conceptualized and organized in a modular way that allows, as much as possible, the ease of integration of recovery modules written by different researchers or airlines. It also allows for inclusion of different crew and aircraft legality rules, making it easier to customize SIMAIR for simulating the operations of any specific airline with specific fleet and crew requirements.

SIMAIR currently simulates operations of legs with planes and crews. A passenger itineraries feature is currently being added to SIMAIR. A more descriptive organization of the communication between different modules is shown in Figure 2.

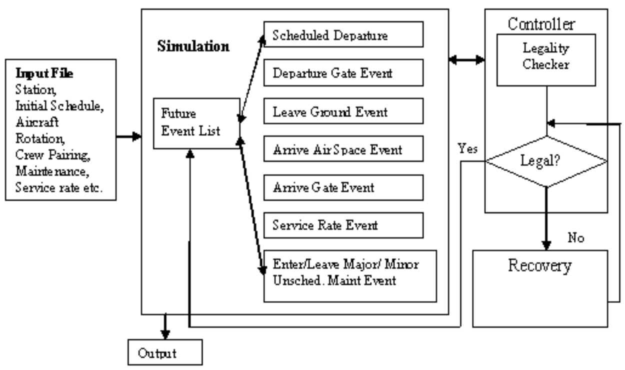

Figure 2: Basic Operational Model of SIMAIR

3.1 Simulation Module

The simulation module models the plane's operation as a sequence of events. One event triggers another leading to a simulation of airline operations.

Each leg in the schedule can be decomposed according to seven events, which are determined by the queuing network in Figure 3.

i. Scheduled departure event – pilot and passenger scheduled to depart from the gate.
ii. Departure gate event - plane pushes away from the gate and begins to taxi to the runway.
iii. Enter runway queue event – plane enters the runway queue of the departure station.
iv. Leave ground event – plane reaches the front of the runway queue and begins its flight.
v. Arrive airspace event – plane enters the airspace queue of the arrival station.
vi. Touch down event – plane reaches the front of the airspace queue and begins to land.
vii. Arrive gate event – plane reaches the gate at the arrival station.

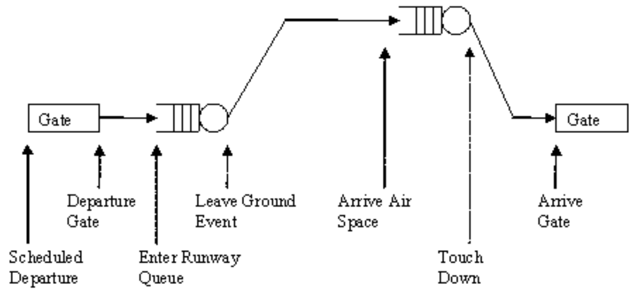

Figure 3: Decomposition of a Leg

In addition to the seven events which decompose a leg above, there are an additional five events

i. Unscheduled maintenance event – plane is required to undergo major unscheduled maintenance. It is a chance event that is generated after departure gate event.
ii. Enter minor unscheduled maintenance event– same as above, but is a minor unscheduled maintenance.
iii. Leave major unscheduled maintenance event– complement of (i), it is generated after plane goes under unscheduled major maintenance, and signals the simulation module that the plane is now ready to fly again.
iv. Leave minor unscheduled maintenance event – similar to (iii), it is the complement of (ii).

Service rate event – an event that changes the service rate of runways of airports simulated. This event changes the duration of plane taking off and landing. In case of service rate event dropping to zero, the airport is closed and no planes can take off or land. The current version of SIMAIR does not explicitly model the effect of other airlines or weather. Such effects are reflected as a change in service rate of the airport.

The SIMAIR model describes the operation of a particular airline or a particular fleet of an airline. The effect that other airlines and weather have on the congestion of an airport is modeled as the service rate of the airport. To illustrate, under normal conditions the service rate of an airport would be high, where more airplanes can land/takeoff. Under conditions considered worse than normal, the rate would be lower.

At each station, planes are modeled to fly-in and fly-out as a first-in-first-out queue. To simulate this action, a runway queue and airspace queue are modeled. The runway queue is for the aircraft beginning their flight that need the runway for takeoff, and the airspace queue is for aircraft that will need the runway to land. These queues are sequences of airplanes that are served at a rate equivalent to that of the service rate of the airport, which in-turn depends on weather and congestion at that particular airport. The queues are assumed to have infinite capacity.

SIMAIR uses random ground time delays, additional block time delays and unscheduled maintenance delays as described previously.

3.2 Controller Module

The simulation module, in the course of execution, calls the controller module at the beginning of every event. The controller module accounts for rules and regulations enforced by bodies like the FAA by introducing the concept of legality. Airline operations are often governed by mandatory rules, such as those proposed by the FAA and those agreed upon by crew unions, regarding the deployment of planes and crew respectively, in operations. To illustrate, one such crew rule is the *30-hour-in-7-days* rule, which specifies that the crew cannot fly for more than thirty hours in any given seven day period of time.

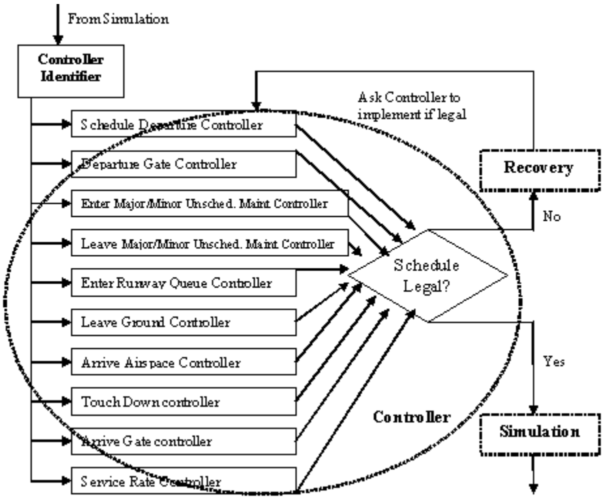

Figure 4: Information Flow through the Controller Module

Each event in the simulation is associated with a corresponding controller in SIMAIR. On occurrence of an event, the corresponding controller checks for the legality of the current schedule. For example, at schedule departure event, one might want to check aircraft legality, for example., whether the aircraft is available or in maintenance and other crew legalities such as the 30-hour-in-7-days rule.

Two types of illegality are identified by the controller module: Immediate illegality and future illegality. Immediate illegality will render the next leg infeasible while future illegality will only cause a problem some time in the future, if the simulation continues as it is.

In the event of illegalities, the controller module will call the recovery module to fix the problem. The controller module will pass the necessary information, such as the type of illegality encountered, the plane or crew involved in the illegality, etc., to the recovery module to allow it to fix the problem.

The controller module is also responsible for checking the feasibility of the proposed changes to the schedule recommended by the recovery module. Some recovery policies might ignore future illegalities passed from the controller module, and only fix the problem for immediate illegalities. Other recovery policies might prefer a "proactive" approach and fix the illegality as soon as it appears (without hindering the immediate execution of the simulation). Since SIMAIR is to be used by different recovery policies, provisions are made such that the controller module will only make sure that the proposed changes ensure that the immediate next leg is legal. If it is not, the controller module will call the recovery module again. The controller module will not call the recovery module again if only future illegality is encountered.

Once the proposed changes by the recovery module are accepted, the controller module will have the additional role of implementing the changes to the operational schedule.

3.3 Recovery Module

A general framework for the recovery module has been established. Currently, a default recovery policy is in place, but users can substitute their recovery policies by following the general framework.

The default recovery policy in place utilizes a set of simple heuristics to recover from the disruptions, and is mostly concerned with resolving immediate illegalities. The set of recovery actions used are:

- Use of reserve crew in event regular crew unable to fly the next leg.
- Deadheading of regular crew to crew bases.
- Pushback of flights when the delay is lower than a threshold and still maintains schedule feasibility.
- Short cycle cancellation of flights in the event that pushback is infeasible.
- Diverting aircraft in the air to alternative airports when destination airport is closed, or aircraft are about to run out of fuel.
- Putting legs "on hold" when a major disruption occurs, such as airport closed down. Flights are prevented from continuing, and only released from on hold status when situation recovers (airport reopen).
- Ferrying of aircraft to stations with maintenance capability to ensure maintenance feasibility.

Conceivably, users of SIMAIR can use some other options to recover, notably utilization of spare aircraft at certain airports, or aircraft swapping. These recovery actions can be coded into SIMAIR.

4 PERFORMANCE METRICS

A series of performance metrics used in evaluating the schedule have been coded into SIMAIR. The output data that are collected at the end of simulation can be categorized roughly into the following types: Summarized data or raw data, leg data or crew data.

Summarized data about schedules such as the number of legs flown, cancelled or late flights, are provided. Flight legs that are late are split further into different levels of lateness.

Summarized data about crew such as the number of reserve crews used, the number of times that crews are deadheaded, the number of times that different crew legality rules are violated, are also provided.

The raw data contains numerous details that are unprocessed. Details about each leg that has flown, and the time when each event occurred for that leg, are provided. These raw data are collected to allow users to trace the various events that happened to the leg. The provision of these raw data gives the user the flexibility to process the data into statistics that are meaningful to them.

5 RESULTS AND DISCUSSION

SIMAIR has been run successfully on a daily-airline-schedule spanning seven days. The test schedule is a subset of a larger schedule provided by a major airline in the USA. The schedule involves 82 aircraft, 335 regular crews and 45 stations. A simple recovery scheme involving steps indicated in Section 3.3 was used to recover from disruptions. In this section we report some of the performance metrics from simulation of this schedule using SIMAIR.

According to the Bureau of Transportation Statistics, a leg is on time if it arrives at the gate within 15 minutes of its originally scheduled arrival time or else it is late. (Cancelled legs and diverted legs are considered late.)

The lateness in arrival can be analyzed by calculating the frequency of late arrival. The number of legs late against the amount of time they are late, has been collected as shown in Figure 5.

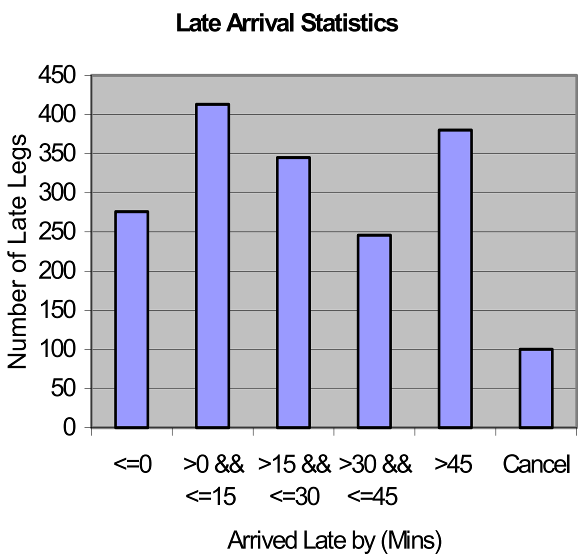

Figure 5: Lateness Histogram

The above statistic gives details of the number of planes that were late by 15 minutes and less, late by 30 minutes and less but more than 15 minutes etc. are collected and reported to give a feel of on-time operations of the schedule.

The simulation shows that close to 6% of the legs (100 of 1680) are cancelled in operations. The ontime percentages for arrivals has been determined using the number of legs late. About 40% of the legs (39% including cancelled and 41% excluding cancelled) were found to be ontime in operations. Data about legs as shown above helps in determining the performance of the schedule with respect to ontime percentage, etc.

For the crew, the data shown in Table 1 has been collected from the simulation. The data collected for the crew includes details like the block time flown by the entire crew, the number of deadheads required, the number of times the crew violated various crew legality rules, etc. The reserve crew flytime is about 12% of the actual block time flown by all crews. The crew had to be deadheaded 122 times and the crew schedule was performing poorly from the *Max Duty Rule* view point with five reported violations. This crew data provides an insight into the robustness of the schedule. This data can also be useful in determining the crew utilization with respect to their pay and credit minutes.

Table 1: Crew Output Data

Total Block Time	225226 (min)
Reserve Crew Calls	85
Reserve Crew BlockTime	26608 (min)
Crew Deadheads	122
DeadheadCrewBlockTime	11062 (min)
#8in24 Violations	10
#30in7 Violations	0
maxDutyViolations	5

Comparison of station data shows that DFW and ORD are the busiest airports with 329 and 294 arrivals respectively. The statistics compare the arrival numbers and the ontime percentages for the two busiest airports in the simulation. Along with these, the data for stations having the best ontime percentage namely TUL and TYS is in Table 2.

Table 2: Best Ontime Percentages

Station	DFW	ORD	TUL	TYS
#LegsArrived	329	294	7	8
#LegsDeparted	329	290	8	8
Ontime%IncludeCancel	0.161	0.178	0.428	0.428
Ontime%ExcludeCancel	0.294	0.326	0.857	0.750

These station details show that DFW is busier that ORD, and also the ontime percentages are less for DFW. Stations TUL and TYS have the best ontime percentages of 0.428 each. The bottle-necks with respect to busy airports that might take longer times in airspace/runway queues.

More details like data aggregated by day-of-week and station, data for late departures and other data can be collected as required from raw output data provided by SIMAIR.

6 CONCLUSIONS AND FUTURE PLANS

A discrete-event simulation model, SIMAIR, has been developed to simulate airline operations and evaluate various performance metrics of an airline schedule. SIMAIR can be used as a research tool to test the robustness of an airline schedule as well as to obtain a feasible schedule in the event of a disruption. The modular structure of the SIMAIR code allows researchers and airlines to implement and test their own recovery policies as well as benchmark against known recovery policies. It has to be noted that SIMAIR provides a framework for testing robustness of schedule as well as for developing recovery schemes. SIMAIR code has been released to various airlines cooperating with the SIMAIR research team and their feedback is currently awaited.

SIMAIR development is proceeding along a roadmap. Plans for the current version include the addition of cargo and an option using a 'human-in-the-loop for recovery operations. More airport details (gate assignment, coterminals, and cargo terminals) are planned for the next version. Looking even further downstream, plans include parallel operations, i.e., many terminals.

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