Strategic and Tactical Functions in an Autonomous Air Traffic Management System

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This paper evaluates, by means of fast-time simulation, performance of a candidate system for autonomous air traffic management. Advancing towards autonomy in air traffic management may be necessary in order for new air vehicle types such as electric Vertical Take Off and Landing (eVTOL) to operate safely and efficiently in airspace shared with conventional traffic. To account for uncertain prediction, autonomous air traffic management was divided into two integrated and coordinated subsystems: strategic scheduling, performed at predeparture, and tactical conflict detection and resolution, performed throughout the flight. The conflict detection and resolution subsystem contained a second tactical scheduling function that applied to flights operating in the airspace near the destination airport. This paper compares and contrasts the two subsystems and uses fast-time simulation to demonstrate the comparisons. A scenario of 54 flights inbound to Newark Liberty International Airport was simulated multiple times with different parameters. The scenario was created using flight plans recorded from the National Airspace System on a low weather, average traffic day in April 2018. Whereas the routes were not changed, the departure times of the flights were modified to increase arrival rates at the Newark runway and arrival meter fixes. Results of the simulations showed that the autonomous air traffic management system was able to safely manage the traffic, even with prediction uncertainty. In addition, they showed the importance of including flight holding maneuvers, in addition to path stretching, in conflict detection and resolution and of coordinating strategic and tactical scheduling. Finally, a tradeoff between absorbing the delay calculated by strategic scheduling on the ground versus in the air showed that taking most of the delay on the ground is cost effective for a simple idealized cost function. However, taking a little of the delay in the air prevented throughput on the runway from dropping for short periods due to trajectory prediction uncertainty.

I. Introduction

A previous paper [1] studied an autonomous Air Traffic Management (ATM) system that was designed to provide airlines greater operational flexibility and control of their flights when they used congested airspaces and airports. The autonomous ATM system consisted of two major subsystems: Collaborative Seamless Manager of Airspace Resources and Traffic (CSMART)[1-4] and AutoResolver (AR)[5-13]. CSMART supported flight operators with self-generating flight plans that satisfied traffic flow management constraints, and AR performed air traffic control operations that kept flights separated.

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Advancing the current ATM system towards an autonomous ATM system as described here would require, among many things, a ground-air data communication system that can uplink trajectories directly into aircraft avionics systems. Such a system is currently being deployed nationally by the FAA. In this research, the autonomous ATM system was configured like the human-centric current ATM system, meaning that current definitions and specifications of air traffic control centers, Terminal Radar Approach Control Facilities (TRACONs), flight plans, routes, Standard Terminal Arrival Routes (STARs), and runways were used. Conventional jet and prop air traffic were studied. Designers of ATM systems for future air vehicles operating in airspaces not controlled by the current ATM system are proposing advanced configurations and specifications that are different. Whereas CSMART and AR can be configured to study future visions, this research was focused on understanding interactions between scheduling and conflict detection and resolution. In addition, whereas AR can be configured for spacing flights for landing based on aircraft weight class and wake vortex spacing rules, that ability was not used in this research to keep runway scheduling, throughput, and capacity simple. A single landing spacing value was used regardless of weight class.

In [1], simulations of the autonomous ATM system were conducted. The scenario for the simulations consisted of 54 flights inbound to Newark Liberty International Airport (EWR). Flight plans for the simulated flights were obtained from actual flight operations that were used in the National Air Transportation System on a low weather, average traffic day. Although routes from the flight plans were not modified, departure times were adjusted to congest the EWR TRACON and runway. Congestion was managed in a two-step process. First, CSMART planned, predeparture, a strategic schedule and ground delayed fights based on the scheduled departure times. This regulated flow of traffic into the EWR TRACON and runway. Then, AR fine-tuned flight spacing by maneuvering flights while they were in the air.

Results of [1] showed that CSMART and AR working in concert could safely manage congestion when there was no uncertainty in the simulations. However, AR was not able to resolve all flight conflicts in simulations where CSMART was turned off and in simulations where trajectory prediction errors were added. It was determined that this was due to excessive flows of traffic into the TRACON caused by strategic scheduling not being present or being degraded by prediction errors. Once too many flights entered the TRACON, AR could not space the flights for landing because there was not enough airspace available to delay flights with path extensions and AR was not allowed to send flights back out of the TRACON. Two approaches for addressing this are expanding AR's library of maneuvers and coordinating CSMART and AR scheduling.

One trajectory maneuver that was heretofore not implemented in earlier versions of AR was the ability to generate holding patterns. This limited the amount of in-air delay that AR could impose on a flight to about 4 minutes. This limitation inhibited AR's ability to throttle traffic flows into the TRACON because it could not give flights enough delay.

AR did not have the ability to coordinate its tactical schedules. Individual AR tactical schedulers were instantiated and applied to the arrival runway and the three arrival meter fixes located to the north, west, and south of the airport. The schedules they produced were independent of each other. For some traffic conditions, the lack of coordination caused flights to be delayed more than necessary before they crossed the meter fixes. This was because traffic flows passing through the meter fixes merge into a single flow that feeds the runway. To meet the throughput limit at the runway, the throughput limits of the three meter fixes were statically set to one-third of the runway throughput. With these settings, when there was high throughput in one meter fix with low throughput in the others, the flights using the high throughput fix were penalized with high delay even though they could have been delayed less due to the low throughput in the other fixes. With coordination between the meter fix and runway schedulers, the throughput in a high traffic meter fix can be dynamically fine-tuned depending on the amount of throughput in the other fixes.

CSMART has the ability to coordinate arrival fix schedules with runway schedules because it connects a flight's arrival fix and runway scheduled times using its predicted transit time. In [1], CSMART schedules were not shared with AR schedules. This was because CSMART built schedules for departure and arrival airports only. It did not build strategic schedules for EWR arrival meter fixes.

The object of this work was to enhance the autonomous ATM system and use it in fast-time simulation to study scheduling coordination between the arrival runway and meter fix, trajectory prediction error, and distribution of departure delay between ground and air. AR was given the ability to assign holding patterns. This greatly expanded AR's ability to delay flights while they were in enroute airspace. In addition, CSMART was configured to calculate strategic schedules for the meter fixes in addition to departure and arrival runways. These strategic schedules were coordinated and shared with AR, which was able to maneuver flights to keep them on track to meet the strategic schedule. With these enhancements to CSMART and AR in place, fast-time simulations were conducted, and results were analyzed. The simulations focused on arrival runway and meter fix schedule coordination, trajectory prediction errors, and cost tradeoffs between ground and airborne delays.

An outline of this paper is as follows. First, the general purpose of scheduling is discussed. Then, the scenario used in the simulations is illustrated. Features of AR and CSMART used in this study are described. An experiment matrix is shown, and results are presented. Finally, future work and conclusions are provided.

II. Scheduling

This section describes scheduling, its purpose in an air traffic management system, and the differences between tactical and strategic. In the autonomous ATM system, CSMART generated the strategic schedules, and AR generated tactical schedules as part of its conflict detection and resolution algorithm. This section reviews the general purposes of strategic and tactical scheduling without elaborating CSMART and AR. Follow-on sections describe their details. Generalized scheduling concepts are helpful for understanding the Experiment and Results sections.

Scheduling in autonomous ATM is used to control arrival rates and departure rates at runways, occupancy rates in sectors, and aircraft spacing at traffic flow merge points. It works by building a "use" schedule for resources that have high demand by flights in the airspace. Examples of high demand airspace resources include arrival meter fixes and runways. A "use" schedule contains a Scheduled Time of Arrival (STA) for each flight that will use a resource. The STAs are calculated such that they satisfy spacing and rate constraints.

Calculating STAs requires predicting Estimated Times of Arrival (ETAs). An ETA is the time a flight is predicted to arrive at a resource given its updated flight plan. The primary constraint that the ETA imposes on the calculated STA is that the STA must be within a given proximity of the ETA. Typically, the proximity is set to allow the flight to arrive at the resource anywhere from slightly early to largely delayed. This constraint ensures that a STA is realistic, i.e., the flight is capable of physically traveling to the resource by the STA.

By definition, ETAs are estimates and are therefore uncertain. Predicting them depends on many uncertain parameters, some of which are wind speed, aircraft parameters, pilot intent, and traffic. Wind speed affects the ground speed of an aircraft. Aircraft parameters such as weight, drag, lift, and thrust, limit the speeds and accelerations that an aircraft can use in cruise, climb, and descent. Generally, information in the flight plan such as route, cruise speed and altitude can be used to infer pilot intent. However, pilots at times and for different reasons deviate from their flight plans. A good example of a pilot deviating from the flight plan is when the flight encounters traffic and the controller, or an automated agent such as AR, asks the pilot to deviate the flight.

Furthermore, because ETAs are derived from ground speed by integration, time errors tend to grow as prediction time horizons get longer. In other words, small errors in ground speed cause large errors in estimated times of arrival for long time horizons. The longer the time horizon, the larger the estimated time of arrival error. Errors in ETAs propagate into calculated STAs. Therefore, STA errors grow as prediction time horizons get longer. These errors can make STAs unrealistic, i.e., flights cannot physically meet their STAs.

The STA accuracy requirements for controlling arrival rates and occupancy rates are lower than those required for spacing flights. Short durations of excessive arrival rates or occupancy rates produced by STA errors may not impact safety, especially when the rates or occupancies averaged over larger durations are not excessive. However, even small deviations in flight spacing immediately violate separation constraints. Thus, scheduling systems are divided into tactical and strategic systems. Whereas strategic systems have long time horizons and are limited to controlling rates and occupancies, tactical systems are limited to short time horizons, generally using a freeze horizon, and are used to control flight spacing.

As noted in the introduction, this paper assumes operations that are similar to those in today's ATM. Designers of future ATM systems seek to minimize errors using different approaches. For example, it is possible to have the flight deck control the aircraft speed to meet a ground speed target. Minimizing ETA errors may eliminate the need for separate strategic and tactical schedules, which would be replaced by a single global schedule encompassing all time horizons and locations.

Table 1 summarizes the differences between strategic and tactical scheduling for this research. Most properties are self-explanatory. The following section explains some in more detail.

Table 1 Strategic vs. Tactical Scheduling

Property	Strategic	Tactical
Instantiation	CSMART	AR
Spatial scale	United States	Terminal airspace
Time horizon	20 minutes to over 6 hours	20 minutes
Control system	Open-loop	Closed-loop
Action	Departure delay	Maneuvers
Purpose	Limit arrival rate	Maintain flight separation
Today's systems	Traffic Flow Management System (Ground Delay Program and Airspace Flow Program)	Time-Based Flow Management (airborne part)

The "Spatial scale", "Time horizon", and "Purpose" properties are related. Because the purpose of tactical scheduling is maintaining flight separation as flights cross the meter fix, their actual crossing times need to closely match their scheduled crossing times. Otherwise, the spacing goal is not achieved, and loss of separation may occur. Working against this goal is uncertainty, which grows with time horizon. To keep tactical scheduling meaningful, its time horizon is limited to approximately 20 minutes, which limits the impact of uncertainty. The 20-minute time horizon is controlled by using a freeze horizon, which is a boundary drawn around the spatial area for which the tactical scheduling applies. As flights cross the freeze horizon, they are assigned a STA at the meter fix. Once the STA is fixed, AR monitors the progress of the flight and closes the loop by maneuvering a flight that lag or leads its STA or is predicted to lose separation.

The "Control system" property refers to how the schedule is enforced. Strategic scheduling is open-loop because the strategic schedule is enforced using departure delay only. No additional adjustments to meet strategic schedule are made to the flight after gate departure. This means that STAs for the runway and meter fixes that were planned in the strategic schedule may not be always achievable due to increasing time errors. On the other hand, tactical scheduling is closed-loop. Once a scheduled time of arrival for a flight has been frozen, air traffic control periodically monitors the flight's progress and maneuvers it if it determines that it will not meet its scheduled time of arrival.

The "Today's systems" property refers to systems in use in today's National Airspace System that loosely fit into this categorization of scheduling systems. Parts of the Traffic Flow Management System (TFMS) system, which include Ground Delay Programs (GDPs) and Air Space Flow Programs, fit in the strategic category, whereas the parts of the Time-Based Flow Management (TBFM) system that calculate scheduled times of arrival and provide controllers with advisories for delivering flights to their arrival meter fixes at their scheduled times of arrival fit in the tactical scheduling category. The part of TBFM that ground delays flights has characteristics of both strategic and tactical. It is strategic because TBFM assigns flights departure delays, and tactical because this TBFM function is also applied to flights departing from airports that are within a specified proximity of the arrival airport.

III. Experiment

This section describes the simulations that were conducted for this paper. The simulations were conducted to explore schedule coordination, trajectory prediction errors, and distributing distribution of departure delays between ground and air. The scenario that drove the simulations, the simulation setup and process, and the experiment matrix are presented.

A. Scenario

All the simulations presented in this work were initialized with one scenario. This was the same scenario used in [1]. Key parameters of the scenario are listed in Table 2. The numbers in parentheses next to domestic departure airport codes denote the count of departures greater than 1 for that airport. All flights arrived at Newark Liberty International Airport (EWR) on runway 22L. There is another crossing runway at EWR that is available for arrivals, but that runway was not used in these simulations.

Table 2 Scenario Parameters

Parameter	Value
Flight Count	54
Simulation Duration	~ 7 hours
Domestic Flight Count	42
International Flight Count	12 (4 south, 2 north, 6 east)

Arrival Airport Code	EWR
Arrival Runway	22L
Domestic Departure Airport Codes	SJC, STL, CLT, DFW, BUF, PBI, CMH, SFO(2), AUS, ROC, MYR, BOS(2), PDX, RDU, GSO, MSN, MKE, RIC, IAH, SEA, RSW, CVG(2), ATL(2), ITH, CHA, CLE, PIT, SAN(2), IND(2), SNA, FLL, TPA, BTV, LAX, DTW(2)

Figure 1 displays the flight routes. The scenario contained domestic flights departing from large airports dispersed across the United States. It also had international flights that began simulation at cruise altitude and speed where their routes intersected the boundary of the United States' airspace. Table 2 lists the international flight counts that entered the airspace from the south, north, and east.

Fig. 1 Routes

All flights approached EWR through one of three arrival meter fixes. Table 3 lists the fixes and the counts of flights using them.

Table 3 Arrival Fix Flight Counts

Arrival Meter Fix	Flight Count
SAX	15
METRO	17
SWEET	22

Figure 2 illustrates the layout of the airspace surrounding EWR. EWR shares its TRACON, N90, with LaGuardia Airport (LGA) and John F. Kennedy International Airport (JFK). N90 is shown expanded in the right side of Fig. 2. The three Standard Terminal Arrival Routes (STARs) and the arrival meter fixes that terminate them are shown. The approach fixes for runway 22L are GIBTE and IDACE. GIBTE is labeled. IDACE, the black dot under GIBTE, is not labeled due to limited space in Fig. 2. The paths drawn in orange are the nominal flight trajectories from the arrival meter fixes to 22L. During simulations, AR used maneuvers to modify these to resolve conflicts. The proximity of EWR to LGA and JFK and the sharp right turn into GIBTE, limited the maneuvers available to AR.

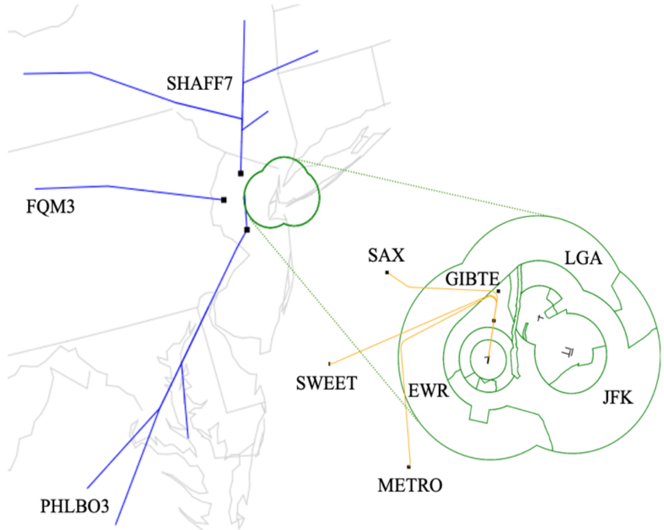

Fig. 2 Layout of EWR Airspace

The scenario was created using historical flight plans recorded on April 26, 2018. On this day, weather had a minimum impact on operations, and traffic volume was average. Flights that landed on 22L at EWR between 18:30 and 20:00 UTC were selected for the scenario. The actual flight plans did not produce an arrival rate at EWR that was high enough to require strategic scheduling. To create a time period with an increased arrival rate, 18:30 to 20:00 was divided into 3 30-minute bins, see Table 4. Flight departure times were adjusted with the objective of moving flights from the first and last bins to the middle bin. The movement process preserved the original landing order at EWR.

Table 4 Actual and Adjusted EWR Arrival Counts in 30-Minute Bins

Time Bin UTC	Actual Arrival Count	Adjusted Arrival Count
18:30 – 19:00	19	10
19:00 – 19:30	19	29
19:30 – 20:00	16	15

Figure 3 shows the actual and adjusted arrival rates as landing counts in sliding 15-minute bins at EWR. Using 70 seconds as the average spacing limit between flights as they cross the runway threshold, the average maximum arrival rate is 12.8 arrivals per 15-minute bin. The adjusted arrival rate peaked at 19 arrivals per 15-minute bin, which was well above 12.8 arrivals per 15-minute bin. Furthermore, it was sustained above 12.8 arrivals per 15-minute bin from 19:05 to 19:25. The adjusted scenario challenged the strategic and tactical schedulers and was used in the simulations.

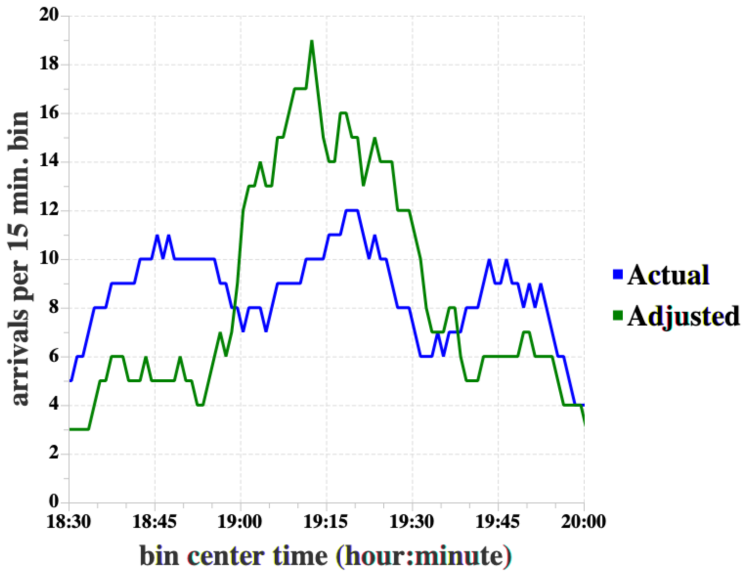

Fig. 3 Actual and Adjusted Arrival Rates and EWR 22L

B. Simulation Tools and Processes

The simulations in this research were conducted using CSMART and AR, the same tools that were used in [1]. For a more in-depth description of these see [1]. The following provides an explanation of how the simulations were set up and of the processes that executed during the simulations. Except for the special cases described in this paper, this was similar to what was done in [1].

The simulations executed in two steps. In step one, CSMART generated the strategic schedule. In step two, the flights were simulated, departing according to the strategic schedule and with AR providing separation services as a surrogate for air traffic controllers. Only one pass per simulation was made through the two steps. CSMART strategic planning was open loop because it did not intervein the flight after giving it a departure delay.

In step 1, departure runways, the EWR arrival runway, and the three EWR arrival meter fixes were resources where CSMART built schedules. Because the scenario included only flights destined for EWR, only one or two flights departed from the same airport. Thus, departure runways were not congested, and there was no departure delay due to departure demand. In a more realistic scenario, departure runways may be congested due to departures destined for airports other than EWR, and this would impose additional delays on EWR departures. On the other hand, all flights arrived at a single EWR runway, and the scenario was adjusted to congest the runway. CSMART found, for each flight scheduled, STAs at its meter fix and on the EWR runway that were properly spaced with other flight STAs. Departure delays were calculated based on the meter fix and arrival runway STAs and transit times. There were transit times for both takeoff runway to arrival meter fix and arrival meter fix to arrival runway. Departure runway, meter fix, and arrival runway STAs aligned with the transit times. This alignment kept the meter fix and runway schedules coordinated. Coordination made more efficient use of the meter fixes and kept pressure on the arrival runway without congesting the TRACON.

CSMART required transit times, which when added to initial runway takeoff times produced ETAs at the meter fixes and arrival runways. Two case were explored: without uncertainty and with uncertainty. In the without uncertainty case, transit times were extracted from the baseline simulation (Base, see Table 6), which was without AR intervention. In this case, transit times, and hence ETAs, do not have uncertainty because they were generated by the same trajectory generation algorithm that was used for simulations. In the with uncertainty case, the transit times were estimated using an algorithm, named the ETA generator, that was different from the trajectory generation algorithm used in the simulations. To calculate ETAs, the ETA generator divided flight routes into climb, cruise, and descent segments. Cruise transit times were calculated using the cruise speed and the distance of the cruise segment. Climb and descent transit times were calculated using an estimated average speed during climb or descent, derived from the cruise speed and takeoff or landing speeds, and the distances of the climb and descent segments. Differences, called errors, between the two ETA generation methods were generated by subtracting the with uncertainty transit times from those without uncertainty. Table 5 lists the error statistics for takeoff to meter fix and meter fix to landing transit times. The errors loosely represent ones that would be present in an operational trajectory prediction algorithm. However, they were not derived by modeling physical uncertain phenomena in the real system, such as winds, pilot actions, and traffic, that cause trajectory prediction errors.

Table 5. Transit Time Error Statistics (minutes:seconds). A positive value means that the with uncertainty transit time was greater, and a negative one means that the without uncertainty transit time was greater.

Statistic	Takeoff to Meter Fix	Meter Fix to Landing
Mean	-0:26	0:56
Standard Deviation	3:41	0:51
Min	-10:43	-2:52
1st Quartile	-2:31	0:39
Median	-0:36	1:01
3rd Quartile	2:49	1:27
Max	9:16	2:41

In step two, simulations used AR to keep flights separated. During post-departure simulation, AR periodically performed conflict detection and resolution every minute of simulation time. Tactical scheduling was part of AR's conflict detection and resolution process.

Independent tactical schedules were generated for the EWR three arrival meter fixes and arrival runway. Thus, there were four tactical schedulers, one for SAX, METRO, SWEET, and 22L. The tactical schedulers calculated STAs for flights during simulation as they crossed freeze horizons. The freeze horizons for the meter fixes schedulers were approximately 200 miles from the fixes, and the freeze horizon for the runway scheduler was chosen at points where the flights crossed the arrival meter fixes. When AR detected that a flight was not going to meet its meter fix or runway STA, it attempted to put the flight back in conformance by maneuvering it. Maneuvers included speed changes, path stretches, holding patterns, and combinations thereof.

Traffic flows from the three meter fixes merged before going to the arrival runway, see Fig. 2. Because meter fix schedules in AR were not coordinated with the arrival runway schedule, their throughput limits were set to be one third the maximum throughput of the runway. This prevented flights from entering the TRACON too closely spaced and avoided holding flights that were waiting for their arrival runway STA. Another approach, which was not done, would have been to make the arrival meter fix throughput limits proportional to the arrival counts in Table 3. Whereas this approach would be more customized to the demand than setting each fix throughput limit equal, it still would suffer from not being dynamic.

AR used holding patterns in enroute airspace to generate, if needed, large delays for flights before they crossed the meter fixes. Holding patterns were not allowed in the TRACON airspace, between the meter fixes and the runway because there was not enough airspace in the TRACON to use holding patterns. Because the arrival meter fixes are located near the border of N90, the arrival meter fix schedulers affected flights operating in enroute airspace and headed towards the meter fixes, whereas the 22L scheduler affected flights operating in N90 and approaching 22L.

C. Simulation Setup

Simulations were setup and executed to explore three issues: schedule coordination, trajectory prediction error, and departure delay. The following describes the items and how simulations were setup to explore them. Table 6 summarizes the setups.

1. Schedule Coordination

Coordination refers to the relationship between the meter fix and runway schedules. As described in Section III.B, the AR meter fix and runway tactical schedules were independent. On the other hand, CSMART departure runway, meter fix, and arrival runway schedules were coordinated.

To study the effect of coordination, a simulation without coordination was compared to simulations with coordination. The without coordination simulation was setup by turning off CSMART and using AR scheduling. The simulation with coordination was setup by turning CSMART on and sending its STAs for the meter fixes to AR. AR overrode its internal meter fix STAs with those from CSMART. The overrode STAs were not adjusted as flights progressed in the air. AR accounted for errors accumulated due to uncertainty by maneuvering flights. If a flight could not physically meet its STA, AR would get it as close to possible to its STA. This was done for meter fix STAs only. For the arrival runway, AR used its internally generated STAs from the tactical scheduler. Thus, meter fix crossing time errors were accounted for by AR in its TRACON management and runway STAs. Two to three times in coordination simulations (with and without trajectory prediction error), if a flight had a large meter fix crossing time error, AR would switch its order with another flight's order in the landing sequence. Table 6 summarizes how AR and CSMART were set up to study schedule coordination. The without coordination simulation was named No_Coor, and the with coordination simulation was named Coor.

The runway and meter fix spacings listed in Table 6 were selected for various reasons. A runway spacing of 70 seconds was selected for AR. This value was selected by executing simulations without CSMART and varying the AR runway spacing. It was found that a 70 second spacing at the runway prevented most flights from conflicting in the TRACON. The few flight pairs that did conflict had widely different flight speeds because one flight was a prop and the other was a jet. AR conflict resolution was able to cleanly, meaning without producing secondary conflicts, resolve these conflicts.

In No_Coor, AR meter fix spacing was set to 210 seconds, which produced one-third the runway throughput at the meter fix. This was done for the reason previously explained in Section III.B.

In Coor, CSMART meter fix and runway spacing was set to 75 seconds. A simulation with 70 second CSMART meter fix and runway spacing was attempted, but it was found that the reduced spacing allowed too many flights into the TRACON, and AR did not have enough airspace to keep them separated.

2. Trajectory Prediction Error

The effects of trajectory prediction errors were studied. Simulations modeling errors were setup by using the ETA generator, see section III.B, in CSMART to calculate ETAs. Simulations not modeling error were setup by using the transit times from the Base simulation to calculate ETAs. Table 6 lists the simulations used to investigate errors. The simulation with error was named Coor_Error, and the simulation without error was named Coor. Sigma, the parameter described in the next section, was used only for the departure delay. For the trajectory prediction error study, Coor_Error with sigma equal zero was used.

3. Departure Delay

The effects of trading off ground and airborne departure delays were studied. As presented in Section III.B, departure delays were derived from CSMART departure runway STAs. A new parameter with values between 0 and 1 and named sigma was introduced. Simulations were executed with different values of sigma where the value of departure delay absorbed on the ground was calculated by multiplying the departure delay recommended by CSMART by sigma. As listed in Table 6, nonzero values were applied only to Coor_Error. Sigma allowed for selecting the distribution of departure delays between ground and air. The portion of departure delay not absorbed on the ground was absorbed, post departure, in the air.

Table 6 Simulation Matrix

Name	CSMART STA Spacing		AR STA Spacing		Error Modeling	Sigma
	runway	meter fix	runway	meter fix		
Base	off	off	off	off	no	0
No_Coor	off	off	70	210	no	0
Coor	75	75	70	Overrode by CSMART	no	0
Coor_Error	75	75	70	Overrode by CSMART	yes	0-1

IV.Results

This section presents the results of the simulations. The metrics used to analyze the results were delay, maneuver counts, and throughput. Results are presented for schedule coordination, trajectory prediction error, and departure delay.

Figures 4 and 5 and Table 7 show delays, throughput, and maneuver counts, respectively. They are used to show trends for the schedule coordination and trajectory prediction error studies presented in sections IV.A and IV.B, respectively. In Fig. 4, the bars denote average delay, and the error lines illustrate positive and negative delay standard deviation bounds. The curves in Fig. 5 show traffic throughput in crossing per 15-minute bin through the SWEET meter fix. Throughput for SWEET is presented because it was the meter fix with the heaviest traffic. Table 7 lists maneuver counts, breaking them out by enroute versus TRACON, purpose, and type. Purpose was divided into Loss Of Separation (LOS) and schedule. LOS meant that AR gave a flight a maneuver to prevent a LOS, and schedule meant that AR gave a flight a maneuver to solve a STA conformance error at the meter fix or runway. At times in the simulation when a flight was detected to have both a separation conflict and a STA conformance error, AR prioritized schedule maneuvers and ensured that the maneuver also resolved the conflict. Type was divided into speed, path, hold, and combinations of path or hold with speed. Speed meant that AR changed a flight's speed, and path meant that AR changed a flight's route by inserting turns of less than 180 degrees. Hold meant that AR inserted a racetrack pattern into the route, where the turns were sized for the flight's speed and the straightaways were sized to achieve a specified delay. Flights only traversed racetracks once.

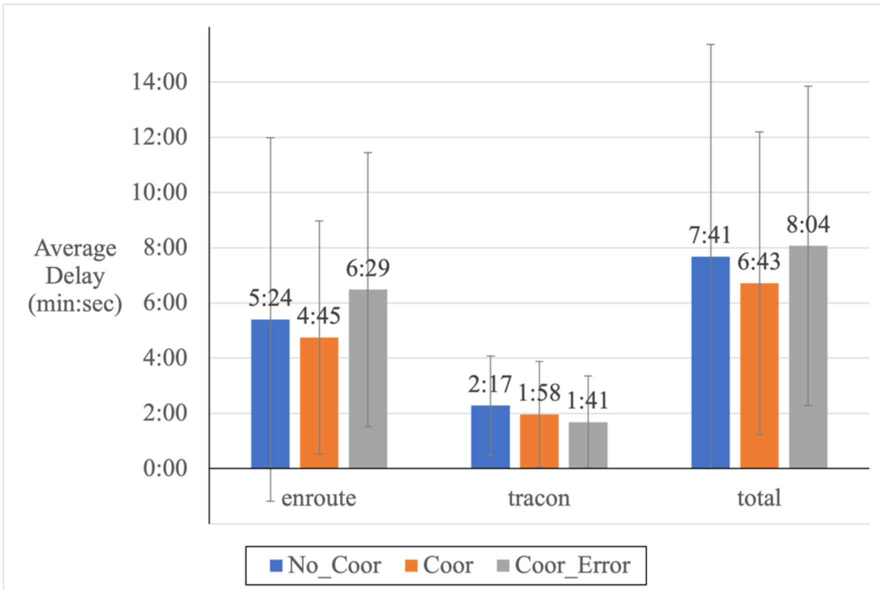

Figure 4 Delay Average and Standard Deviation

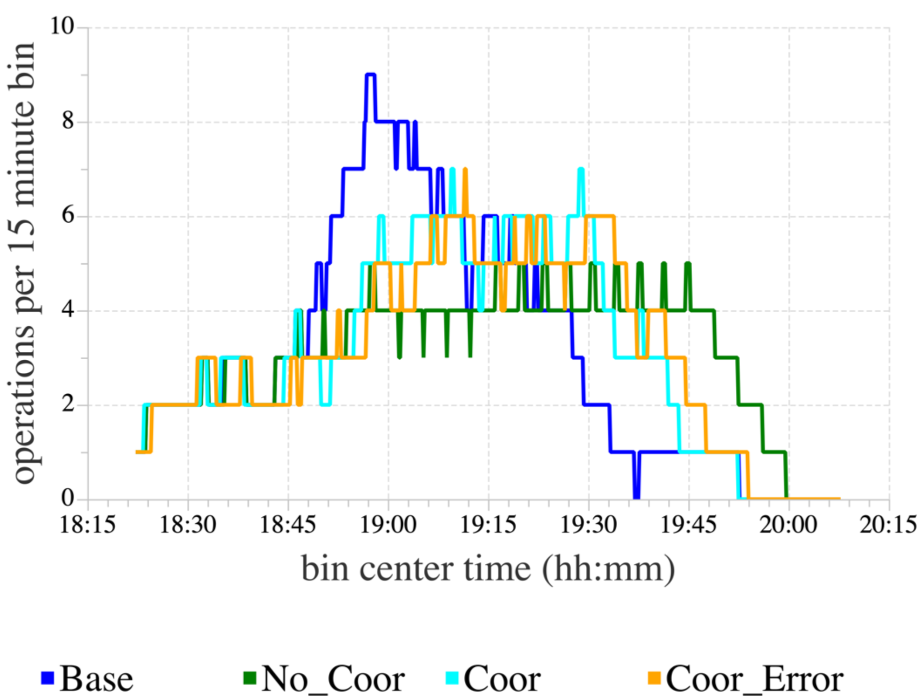

Figure 5 SWEET Throughput

Table 7 Maneuver Counts

		No_Coor	Coor	Coor_Error
Total		86	94	95
Enroute		42	58	56
Type	speed	6	11	8
	path	9	19	9
	speed & path	13	4	9
	hold	7	13	11
	speed & hold	7	11	19
Purpose	LOS	6	5	4
	scheduled	36	53	52
TRACON		44	36	39
Type	speed	7	5	7
	path	1	1	4
	speed & path	36	30	28
Purpose	LOS	0	0	0
	schedule	44	36	39

A. Schedule Coordination

The effect of coordinating meter fix and arrival runway schedules was analyzed by comparing results of No_Coor and Coor. According to Fig. 4, average delay was less for Coor. Similarly, delay standard deviation was smaller for Coor. The differences in delays between the two cases are smaller in the TRACON than in the enroute. This was because the TRACON airspace is much smaller than the enroute. Furthermore, holding patterns were not allowed in the TRACON.

Figure 5 shows throughput across the SWEET meter fix. The Base curve was the demand. It represented an idealized throughput with no limits on flight separation and arrival rate. The demand at 19:00 was 9 operations per 15-minute bin. That rate exceeded the No_Coor spacing limits at the meter fix, and that rate combined with throughput from the other meter fixes exceeded the runway limit. No_Coor had a static limit of 4.2 operations per 15-minute bin (900 sec/210 sec), as observed in the figure. This limit was set to protect the runway from receiving too much traffic to quickly from SWEET and the other two fixes. Although Coor had a static limit of 12 operations per 15-minute bin (900 sec / 75 sec), its throughput was dynamically coordinated with the throughputs of the other meter fixes to protect the runway. The Coor case allowed more throughput during the high congestion duration of 18:45 to 19:30. The additional throughput translated into less delay.

Throughputs across the other fixes did not have the high demand of SWEET. Plots for the other meter fixes were not included in the paper because at those fixes there was little difference in throughput between No_Coor and Coor.

According to Table 7, total maneuver counts were more in the enroute for Coor. This was partly because more maneuvers for schedule were given to flights passing through the low traffic meter fixes (METRO and SAX), see Table 8. These were needed when schedules were coordinated. In the TRACON, Coor had fewer maneuvers. This was because Coor was able to solve runway schedule issues upstream of the TRACON. This cannot happen in No_Coor because the meter fix schedulers lack information about the runway schedule.

Table 8 Schedule Maneuvers by Fix (hold/total)

	No_Coor	Coor
METRO	3/7	6/17
SAX	4/11	7/15
SWEET	6/18	11/21

There were no maneuvers observed for avoiding LOS in the TRACON. This was because scheduling at the meter fixes was properly spacing flights as they entered the TRACON and, hence, regulating traffic flow. There were a few maneuvers for LOS in the enroute, and disproportionately more maneuvers were for schedule. This was because scheduling efficiently kept both flights separated and prevented traffic from getting too heavy.

B. Trajectory Prediction Error

Trajectory prediction error was analyzed by comparing Coor and Coor_Error. According to Fig. 4 in the enroute and total categories, Coor_Error had higher average delay and larger delay standard deviation. This was because trajectory errors required additional schedule maneuvers to keep flights on track to meet their STAs. In the TRACON, Coor_Error had smaller average delay. Fig. 5 helps explain this.

Although difficult to see in Fig. 5, Coor_Error had slightly lower throughput across SWEET. This can be seen by noting that Coor peaks at 7 operations per 15-minute bin twice, whereas Coor_Error only peaks once. In addition, Coor throughput begins falling at 19:33, which is a little earlier than when Coor_Error begins falling at 19:36. This small reduction of throughput during the high congestion duration meant that Coor_Error restricted the flow of flights into the TRACON a little more than Coor, which translated into a little less TRACON delay, see Fig. 4.

According to Table 7, Coor_Error had more maneuvers in the TRACON, with only two less in the enroute. The maneuver increase in the TRACON was due to trajectory errors causing flights to miss their STAs at the meter fix. The root mean square error of the differences between meter fix STA and actual crossing time for Coor was 58 seconds and for Coor_Error was 1 minute 26 seconds. Larger STA conformance errors for Coor_Error meant that flights in the TRACON needed more maneuvers to get properly spaced for the runway.

Although Coor_Error had 2 less total maneuvers in enroute, it had 6 more hold type maneuvers (counting both hold and speed & hold). The higher average delay of Coor_Error was due to the additional hold maneuvers because hold maneuvers produce larger delays.

C. Departure Delay

The sigma parameter was introduced to allow for distribution of departure delays between air and ground. A series of simulations was executed with sigma values of 0, 0.25, 0.5, 0.75, and 1.0. All simulations included coordination and trajectory prediction errors, Coor_Error from Table 6. A new metric, named cost, was introduced. Cost was defined as ground delay plus airborne delay multiplied by two. Airborne delay was simply estimated to be twice the cost of ground delay because airborne delay consumes more fuel. Figure 6 presents the results. Ground delay increased and airborne delay decreased with increasing sigma. Cost was lowest for a sigma of 0.75. Total delay was approximately flat, with a slight increase for sigmas greater than 0.75.

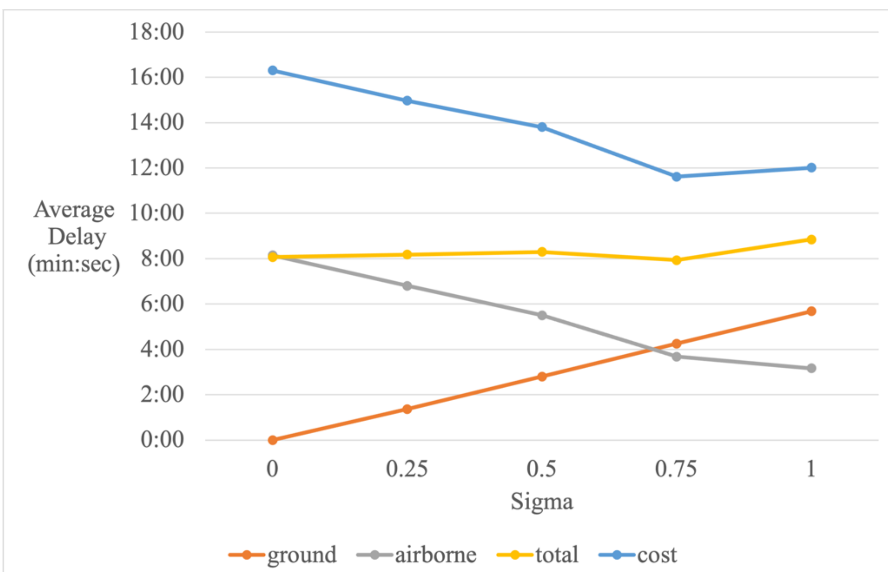

Figure 6 Average Delay versus Sigma

V. Future Work

The results in this paper were produced by the current instantiations of AR and CSMART. This section proposes future work that would advance AR and CSMART towards being ready for field operations. Whereas this research used a scenario containing conventional jet and prop arrivals at EWR, AR and CSMART are autonomous systems also applicable to Electric Vertical TakeOff Landing (eVTOL), Unmanned Aerial System (UAS), and High Altitude

Low Endurance (HALE) aircraft. In addition, AR and CSMART could enable advanced operational procedures for conventional traffic that save fuel burned and reduce emissions.

In coordinated simulations, STAs for the meter fix were passed to AR. The STAs were produced by CSMART predeparture. Due to trajectory prediction uncertainties, there were errors in the STAs. At times, the errors created STAs that AR could not satisfy by giving flights maneuvers. Future work could explore reevaluating the strategic schedule for flights while they are operating in the air. By doing this, STAs that AR cannot meet could be adjusted. The FAA's Time-Based Flow Management (TBFM) system, used by human air traffic controllers, does this for flights that are outside the freeze horizon.

In this research, uncertainty was modeled by using different trajectory generators (the ETA Estimator and the simulation trajectory generator) to calculate ETAs. This created errors in the STAs. Uncertainties could be modeled more realistically by adding wind and pilot models to the simulation. A realistic wind model would be used in the simulation trajectory generator, and a forecast model would be used in CSMART's ETA generator. Furthermore, a pilot model could be added. The pilot model would create differences in the cruise speeds and altitudes and climb and descent rates. Once realistic uncertainty models have been added to the simulation, Monte Carlo studies could be conducted. To do Monte Carlo, AR and CSMART would need to be made more robust so that they could accommodate more off-nominal cases, which they would be exposed to when executing many scenarios with random inputs. In addition, the simulation data collection and analysis tools would need improvements to accommodate much larger amounts of data.

In this research, EWR was the only arrival airport, and only one arrival runway at EWR was modeled. Future simulations could increase the number of arrival airports and number of arrival runways at a single airport. One way this could happen is by including JFK and LGA arrival traffic in the simulation because they are both large airports that share the N90 TRACON with EWR.

CSMART scheduling could be updated to include uncertainty. In this research, CSMART created STAs that were deterministic in the sense that they were a single time. Future research could study making the STAs probabilistic. A probabilistic STA would no longer be a single time. Rather, it would be a time interval such that a flight would be able to use its resource at any time during the interval. A new approach for constraining rates and separations that uses probabilistic time intervals instead of deterministic times would need to be developed.

VI. Conclusion

Simulations of a scenario of 54 flights arriving at Newark Liberty International Airport were executed. The simulations illustrated autonomous scheduling and conflict detection and resolution working together to keep flights separated and keep traffic from getting congested. The simulations included two scheduling systems: tactical and strategic. Tactical scheduling was used as part of conflict detection and resolution to assist with keeping flights safely separated. Strategic scheduling was done predeparture and used to calculate departure delays such that the arrival rates at the EWR runway and arrival meter fixes were limited below a threshold.

The scenario was created using actual flight plans recorded from real operations in April 2018, a low weather, average traffic day. Although the routes in the flight plans were not changed, the departure times were modified to create a higher arrival rate at EWR. The higher arrival rate created the need for strategic scheduling and predeparture delays.

Relative to a past study [1], several enhancements were made to the simulations. AR's conflict detection and resolution system was enhanced to include holding patterns. The strategic scheduling system scheduled times for both arrival meter fixes and the runway, as opposed to only the runway. Errors in the ETAs used by strategic scheduling were modeled. Meter fix scheduled times of arrival from strategic scheduling were given to the conflict detection and resolution system.

Results of the simulations showed that the autonomous ATM system was able to safely and efficiently manage a contrived high arrival rate traffic scenario with and without strategic scheduling and trajectory prediction errors, which was an improvement from the results in [1]. All conflicts were resolved in all the simulations. Delays, maneuver counts, and throughputs for the simulations were analyzed. Delay maneuvers that included path stretches, holding patterns, and speed changes enabled the conflict detection and resolution system to complete the scenario without pre-departure delay. Coordination between meter fix and runway schedules efficiently balanced throughput across the meter fixes and reduced average delay, with the need for extra schedule maneuvers for traffic passing through the low demand meter fixes. ATM with no predeparture delay was accomplished at the cost of many holding patterns in the New York airspace and large airborne average delay. Adding predeparture delays to ATM reduced average airborne delay, with little increase of total delay. If the cost of airborne delay is two times the cost of ground delay, the minimum cost strategy is to absorb 75% of predeparture delay on the ground and 25% of departure delay in the air. Using uncertain ETAs in ATM increased average delay and delay standard deviation, as well as the number of maneuvers required to keep aircraft separated.

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