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An Integrated Collaborative Decision Making and Tactical Advisory Concept for Airport Surface Operations Management

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Surface operations at airports in the US are based on tactical operations, where departure aircraft primarily queue up and wait at the departure runways. There have been attempts to address the resulting inefficiencies with both strategic and tactical tools for metering departure aircraft. This paper presents Spot And Runway Departure Advisor with Collaborative Decision Making (SARDA-CDM): an integrated strategic and tactical system for improving surface operations by metering departure aircraft. SARDA-CDM is the augmentation of ground and local controller advisories through sharing of flight movement and related operations information between airport operators, flight operators and air traffic control at the airport. The goal is to enhance the efficiency of airport surface operations by exchanging information between air traffic control and airline operators, while minimizing adverse effects on stakeholders and passengers. The paper presents the concept of operations for SARDA-CDM, describing both the strategic and tactical components. Then the preliminary results from testing the concept in a real-time automated simulation environment are described. Results indicate benefits such as reduction in taxiing delay and fuel consumption. Further, the preliminary implementation of SARDA-CDM seems robust for two minutes delay in gate push-back times.

I. Introduction

Surface operations at airports in the National Airspace System (NAS) are based on tactical operations, with aircraft often being controlled reactively. Although there are variations in procedures at different airports, essentially departure aircraft are moved from gate to runway whereas arrival aircraft are moved from touch-down to the gate. There are numerous steps involved in these processes with some degree of connectivity in steps. However, there is a lack of strategic planning in airport surface operations. Further, there is very little connection between surface operations and terminal and en-route operations. Although constraints in terminal and en-route flows are transferred to surface during the reactive control, there is a lack of strategic planning during this entire process.

Difficulties in strategic and tactical planning in airport surface operations have received some attention in research in the recent years. Recently, concepts for managing departure aircraft on taxiways and in runway queues have been explored as a means for reducing delays, fuel consumption and emissions[1-6]. These concepts can be divided into two broad categories: Air Traffic Control Tower (ATCT) based and airline based.

ATCT-based concepts provide “advisories” to ATCT controllers at the airport, specifically to the ground controller (broadly responsible for taxiway movements) and the local controller (broadly responsible for departure and arrival aircraft on runways). One such concept is based on controlling the rate of aircraft being released in to the taxiways by the ATCT controllers[6], as well as the number of aircraft in runway queues. In this rate control concept, rate advisories are provided to the ground controller only. Another concept, Spot And Runway Departure Advisor (SARDA), gives aircraft specific sequence and time advisories to ATCT to reduce the number of aircraft on the taxiways and runway queues[3,4]. In the SARDA concept, advisories are provided to both ground and local controllers.

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Both the rate control and SARDA concepts are based on moving the delay from the taxiways and runway queues to the ramp area by providing guidance to the ATCT, and do not cause a reduction in overall delay. Further, they are both "tactical" tools, which respond to the current traffic scenarios with little strategic planning.

Another set of concepts reduce the number of aircraft in taxiways and runway queues by altering the push-back times for departure aircraft; these alterations are done in collaboration with the airlines. One such method, called Collaborative Departure Queue Management (CDQM), manages the length of the runway departure queues by giving the flight operator an allocation of slots to enter the taxiways[1,2]. The assignment of the slots is done through a "ration by schedule" approach, which effectively is a first-scheduled-first-serve approach. Another method with some similarities to CDQM was developed and implemented at the John F. Kennedy Airport in New York, and is currently under use[5]. The method was developed and implemented in response to the potential disruption due to a five month closure of one of the main runways for maintenance in 2010, but its use continued after the runway was re-opened. As in CDQM, the slot allocation is conducted using ration by schedule. The slots for gate push-back are assigned two hours in advance, and any swaps or changes in this allocation are managed by the "slot allocation manager," a neutral third party. The idea behind both these approaches was to hold aircraft at the gate or pre-assigned holding pads with engines off as much as possible, reducing the delays on the taxiway as well as the fuel consumption and emissions. Compared to the above ATCT advisory based tools, these airline Collaborative Decision Making (CDM) tools are strategic in nature. Moreover, different aircraft have different runway usage constraints; defining a single slot size for all aircraft risks under-utilization of the runway or congestion at the runway even under departure metering.

This paper presents an integrated concept that combines the advantages of the tactical ATCT advisory based system like SARDA with a strategic CDM based system: SARDA-CDM. *SARDA-CDM is the augmentation of ground and local controller advisories through sharing of flight movement and related operations information between airport operators, flight operators and ATC. The goal is to improve airport surface operations by maximizing available airport and airspace capacity while minimizing adverse effects on stakeholder, passengers and the environment.* In this paper, we describe the concept of operations of SARDA-CDM, focusing on the timeline of events, the information flow and the benefits to the stakeholders. The goals in this paper are two-fold:

- The SARDA-CDM concept is described, which builds on previous work on tactical advisories for ATCT. The previous work on tactical advisories moves the delay from the runway to the spot[4], and SARDA-CDM aims to move the delay from runway queues to the gate to provide benefits to the airlines in fuel savings and potentially better connections for passengers. The concept includes sharing data between ATCT and airline operators (including updated gate push-back readiness and ATC constraints due to weather), which enables these benefits.
- Results from real time simulation experiments are presented to gauge the effect of airline non-compliance on the SARDA-CDM push-back operations. The effect of the non-compliance on runway usage is shown, and the delay and fuel reduction benefits are evaluated. The push-back non-compliance is modeled as gate push-back uncertainty or deviation from SARDA-CDM provided advisories.

The rest of the paper is organized as follows: Section II gives a brief overview of current day operations, and the potential benefits of an integrated system like SARDA-CDM. Section III provides a brief concept of operations for SARDA-CDM, describing both the strategic and tactical parts. Section IV presents the results from the preliminary benefits assessment of the SARDA-CDM concept through real time simulation. Section V gives conclusions and the directions for future work.

II. Current Airport Operations

In the NAS, the domain of surface operations includes all activities before a departure aircraft takes off and is handed over to the TRACON, and all activities after an aircraft lands. Figure 1 shows the layout of the various elements of surface operations at the Dallas/Fort Worth Airport (DFW). The ramp area has all the gates where the passenger and baggage loading and off-loading take place. Movement within the ramp area is controlled either by a ramp operator, flight operator or a third party. Taxiways, runways and other areas under control of the Air Traffic Control Tower are called the movement area. In some situations, gate push-back moves the aircraft directly on the taxiway. These gates are then considered in the movement area. Spots are defined as the boundary marking the transfer of control from ramp to movement area or vice versa. A more detailed description of these can be found in Ref. 7.

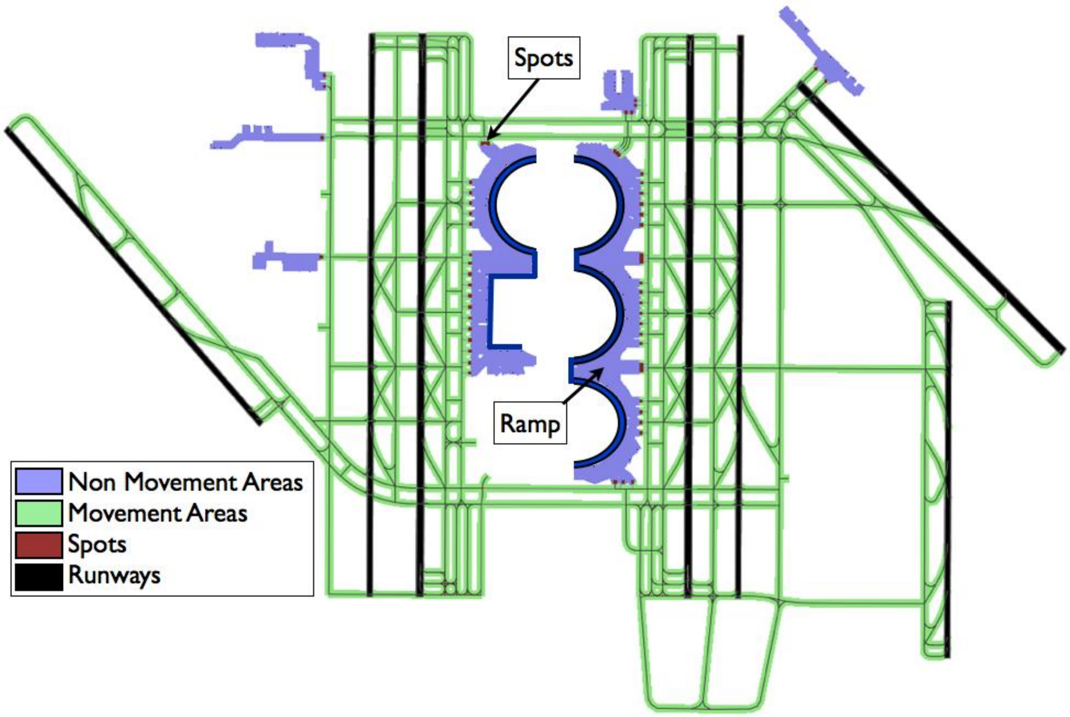


Figure 1: Depiction of various geographical and operational sections at the DFW airport

At almost all large airports in the NAS, the ramp area is managed either by the Flight Operator, Airport Operator or a third party designated by the Airport Operator. Close to the scheduled gate push-back time, departure aircraft convey push-back readiness to the ramp control and get clearance to go to the spot. At the spot, the ATC ground controller issues instructions for taxiing to the assigned runway. There is some evidence to suggest that a lot of these instructions are based on a first-come-first-served basis[8]. In almost all cases, the ground controller releases the aircraft as soon as they get to spot to line them up next to the departure runway. Ground controllers try to sequence the aircraft on the taxiways to some extent to efficiently meet separation criteria at departure fixes as well as wake vortex separation. However, in the case of dense and large departure banks there is little opportunity to do this sequencing. Queued up aircraft next to the runway are handled by the local controller while satisfying all separation criteria. Arrival aircraft landing at the airport are handled by the local controller, and if needed, cross the departure runway based on local controller instructions. After such crossings, the aircraft is handed over to the ground controller who taxies the aircraft to the spot to be handed over to the ramp controller.

The process of getting the departure aircraft out of the ramp and queue up next to the runway (hurry and wait[7]) is a source of inefficiencies in current day operations. With proper and timely information exchange and planning based on these considerations, a lot of the delays at the runway can be transferred to the gate/ramp area. This has many potential benefits, including but not limited to increased efficiency in surface operations, reduction in fuel usage and better connections for transferring passengers. The information exchange and planning process can have some other benefits, like improved predictability in departure take-off times. Ongoing work at FAA seeks to identify some of these benefits and the mechanisms to realize them[7]. SARDA-CDM is a step in this direction, providing information exchange and advisories to the airline operators and ATCT controllers.

III. Brief SARDA-CDM Concept of Operations

The SARDA-CDM system is an augmentation of the previously developed and tested SARDA[4] system for providing tactical advisories to the ground and local controller. Central to the SARDA system was the use of the Spot Release Planner (SRP)[9], a method to provide metering advisories, such as the spot release times for departure aircraft. Spots are physical regions at the airport where the control of a departure aircraft transfers from the ramp/airline to the ATCT ground controller. SRP is a two-stage algorithm: The first stage is a runway scheduler[10,11], which gives the best sequence and times for runway usage by a set of departure aircraft ready for take-off and arrival aircraft waiting to cross the same departure runway. The second stage of the SRP determines times to release aircraft from assigned spots to meet the optimal departure schedules. This scheduling system is called the SARDA-CDM SCHeduler (SCH). It should be noted that SCH is airport specific; some airports will have multiple runways with some degree of inter-dependence in operations, some airports might have multiple runways which can operate independently and others might have separate arrival and departure runways. The runway scheduler in the first stage of SCH is tailored to the runway layout as well as the runway configuration. The second stage of the SCH is tailored to the airports' taxiway layout.

The framework of any concept is built upon a set of assumptions and requirements, and following are the assumptions made for SARDA-CDM. It should be noted that the data inputs prescribed below are to the SARDA-CDM system. The interface for presenting this data to stakeholders and which parts of the data are shown are topics for ongoing research.

- Ramp area operations are managed by airlines or airport authorities and, therefore, ATCT does not have direct control of gate push back for departure aircraft.
- The Ground Controller has authority to hold departure aircraft at spots or holding areas within a specified time interval before the aircraft are cleared to move into taxiways.
- Voice is still the main means of communication between ATCT controllers and pilots.
- Aircraft position data may not be available in the ramp area through a surface surveillance system. However, the actual gate push-back time for departure aircraft is known. Aircraft position data at the spots and the movement area is available through ASDE-X, with the assumption that the current accuracy levels in ASDE-X would be sufficient.
- Prediction of arrival times of departure aircraft at runway queue entrance is available. In the current implementation as presented in Section IV of this paper, we use predictions based on nominal unimpeded travel from scheduled gate push-back to the runway. This could be changed in the future, and better prediction models can be used.
- For the cases where arrival aircraft cross the departure runway, prediction of earliest runway crossing time is available. These can be inputs from a system like TMA.

The SARDA-CDM system consists of a strategic tool which is primarily for airline operators, and a tactical tool meant for the ATCT. Although the end users for the strategic and tactical parts might be different, it should be noted that data are exchanged between the two parts. Moreover, SARDA-CDM facilitates information sharing between the different stakeholders, and this will be described in detail in a later section. The following is a description of the strategic and tactical tools within SARDA-CDM.

A. SARDA-CDM Strategic Planning Component (SPC)

The SARDA-CDM Strategic Planning Component (SPC) is essentially the CDM component that provides a mechanism for the airline operator to share data and preferences with the SARDA system. Central to SPC is the definition of the planning horizon, planning window and planning buffer: *the SPC planning window* is the size of the time window for which the planning is conducted. SPC does planning in non-overlapping time periods with the size of the time periods being the planning window. *The SPC planning horizon* is the "look-ahead" period for planning. It represents how far in advance from the current time is the plan put in place. *The SPC planning buffer* is the buffer time built around the planning horizon to allow for airline responses to the plan; this is decided in collaboration with the airline operators. For example, if the current time is 9:55 am, then a planning horizon of 30 minutes with a planning window of 15 minutes and planning buffer of 5 minutes means the plan for 10:30 am to 10:45 am is developed and communicated to the airline operators at 9:55 am for their response, and is "locked" at 10:00 am. For the purpose of this paper, a planning window of 15 minutes, a planning horizon of 30 minutes and planning buffer of 5 minutes are assumed. These numbers would be tailored to each airport depending on the variation in surface traffic movement, limitations on the use of the scheduler for larger time windows (due to computational complexity) and the inputs of the airline operators.

The following is the timeline of events for a typical scenario under SPC. It should be noted that the following is developed for a generic airport with multiple carriers. Since each airport has its unique structure and issues, the concept might need to be modified accordingly. Further, one major modification would be for hub airports where one airline is the dominant carrier. We address this at the end of this section.

1. SPC operates on non-overlapping planning windows (assumed to be 15 minutes here). In collaboration with flight operators, gate push-back times for departure aircraft are assigned in 15 minute planning bins.

2. The planning horizon is assumed to be 30 minutes [note that the planning horizon could be anywhere from 2 hours (as in the JFK CDM system[5]) to 30 minutes before the scheduled push-back time for the departure aircraft].
3. With a planning buffer of 5 minutes, inputs are sent to the SCH to schedule for that bin 35 minutes before the start of the planning bin. These inputs include:
    - Scheduled gate push-back times for departure aircraft falling within this bin, along with all relevant details about the flight including weight class, departure fix, destination, runway assignment etc.
    - Flight operator inputs on estimated push-back times for the above flights.
    - Traffic Management Initiatives (TMIs) for relevant flights in the planning bin. These could include Ground Delay Program (GDP) based constraints or weather-based constraints. In many airports today, airlines do not have access to this data real time, and this data would be coming in from the tactical component described later. This is one of the ways SARDA-CDM enables data sharing.
    - Preferred times for flights from the previous planning bins spilling into the current bin.
4. **<u>SPC Stage 1</u>**: In this stage, based on the above inputs:
    - Spot release times are generated using the SCH. These times are then passed to the flight operators as a time window Δ_{SR}. The size of the time window is predetermined (say 60 seconds). Along with the time window, a *latest gate push-back time* (say t^*_{pb}) is also passed to the flight operators. The latest gate push-back time is calculated by subtracting "nominal" ramp taxi time from the SCH generated spot release times. We define this time as the marker for compliance: if the aircraft pushes back at any time after this, it is treated as non-compliance. Push-back before this time is still compliance. This information (Δ_{SR} and t^*_{pb}) is not public; every flight operator can see the time windows for their aircraft only. Further, to prevent longer delays at the gate, t^*_{pb} is capped to a certain value within the scheduled gate push-back time. Currently, the airline on-time performance metric includes time spent at the gate beyond 15 minutes from the scheduled gate push-back time[§]. In the same vein, the limit on t^*_{pb} could be 15 minutes from scheduled push-back time.
    - Flight operators either accept these times, request newer times for specific flights, switch flights within their fleet (intra-airline substitution) or negotiate with another airline to switch times (inter-airline substitution). SPC provides mechanisms for all these options, including a Graphical User Interface (GUI) for these exchanges. In the case where intra-airline substitution is sought, the opportunities for substitution are presented anonymously; this is similar to current procedures in the Ground Delay Program (GDP). The development of this GUI and the "flight switching" mechanism is ongoing research at the NASA Ames Research Center. The acceptance of the times or request for alternate ones is a prerogative of the flight operator; a detailed ramp management utility can be developed to aid the flight operators in this decision making. However, such a utility would be independent of the SPC system. The flight operator either uses the ramp management utility or certain rules of thumb to interact with the SPC GUI. These decisions need to be taken by the flight operator within a certain time limit, which is defined by the planning buffer.
    - Acceptance, request for changes or substitutions are inputs into the SPC for the next stage.
5. **<u>SPC Stage 2</u>**: Once the flight operators have given their inputs based on the results of the previous stage, Stage 2 of SPC commences. SCH is run again, with the above inputs from flight operators augmenting the previous inputs for the scheduler. Updated times at the end of this are communicated to all the flight operators. (<u>Note</u>: The actual release from the spot by the ground controller would not necessarily be at this time. The actual release would be within a window of the communicated Δ_{SR}, for example within one minute before but no later than one minute after the communicated spot time)

When the actual realization of the planning bin happens, there are three possible cases:

a. Aircraft pushes back to get to the spot earlier than required. For this, depending on airport structure and the available ramp area space, there are two options based on the size of the ramp area:

[§] Code of Federal Regulations (CFR) Title 14-Aeronautics and Space, Chapter II, Part 234 – Airline Service Quality Performance Reports

i. If the ramp area is sufficiently large, the holding area is defined within the ramp and the ramp controller sends these aircraft to such holding area, making sure that they arrive for spot release in time. This holding area *should not* work in a first-in-first-out manner; any aircraft can get out of the holding area at any time.

ii. If the ramp is small, holding areas are defined on the taxiways. The ground controller releases the early aircraft from the ramp as soon as they get to the spot, and then takes them to the holding area. The aircraft are then released from this holding area to meet the estimated runway times on which the spot times were based. The movement to the holding area depends on how early the flight is available; if the flight is not too early and there is no other flight that might need that spot, the early flight can be held at the spot itself.

In both the above scenarios, the estimated time to be spent in the holding area can be communicated to the pilots over voice, either by the ramp control or even the ground controller depending on who is doing the holding. This is another aspect of data sharing enabled by SARDA-CDM. This would enable the pilots to switch off the engines in the holding area, enabling fuel savings and emission reductions.

b. Aircraft push-back such that the spot release time window (Δ_{SR}) can be met.

c. Aircraft push-back such that they would be late in meeting the spot release time window. For such a case, the aircraft are given spot release when possible through the tactical component and the deviation from t_{pb}^* is noted.

For this concept, an additional metric is proposed as compared to the current on-time performance metric (gate push-back delay of more than 15 minutes published publicly[**]). The new metric would be time spent at gate beyond t_{pb}^*. To avoid large values of t_{pb}^* being set during the planning phase, we defined a limit on the difference between t_{pb}^* and scheduled gate push-back time, which could be 15 minutes or more. This would prevent large gate waiting times, and the limit would depend on the airport and stakeholder inputs

Given any kind of gate release advisory for the airlines, there are two possible "negative" outcomes: First, the flight could be late in meeting the gate times, with these deviations having an adverse effect on runway usage. In SARDA-CDM, this is discouraged by using delay from t_{pb}^* as on-time performance metrics which would be released periodically in a public forum. Second, there is a potential to "game" the system by pushing back early to get to the spot queue early and be at the head of the queue, thus influencing the sequence at the runway. In the SARDA-CDM system, this is overcome by using holding areas in the ramp area or on taxiway, as explained above. Moreover, holding till the right time at the gate is beneficial for airlines since it reduces the fuel spent in taxiing.

B. SARDA-CDM Tactical Advisory Component

The SARDA-CDM Tactical Advisory Component (TAC) is the ATCT component, which provides advisories to the controllers. The outputs of this component are spot release advisories for the ground controller (including time and sequence) and runway usage advisories for the local controller (sequence of runway operations, including take-offs, landings and active runway crossings where applicable). The outputs are "advisories" since it's the controllers' discretion to use them as is or change them and input the change in the system. Further, an interface for the Traffic Management Coordinator (TMC) would also be built into TAC, which facilitates the inputs of airport constraints like runway configuration change or taxiway closure, or for manually feeding flight specific constraints like weather related delays.

TAC builds on the previous work towards tactical advisories for the ATCT[3,4]. A key component of TAC is the interface for the controller. In previous research, timeline and plan-view based interfaces have been explored, where the advisories are displayed within the timeline or as text within the data-tag on plan view. However, Electronic Flight Strips (EFS) based advisories are also possible, with the sequencing advisories being given in the stacking order of the strips, and the timing advisories being displayed through color changes of the strips. Such an EFS system for TAC is currently under investigation at the NASA Ames Research Center.

The inputs to TAC are similar to the inputs when SCH is used in SPC:

- Gate push-back times for each aircraft from SPC, along with all relevant details about the flight including weight class, departure fix, destination, runway assignment etc.
- Spot times for the flight from SPC, on which the agreed upon t_{pb}^* values are based.

[**] Code of Federal Regulations (CFR) Title 14-Aeronautics and Space, Chapter II, Part 234 – Airline Service Quality Performance Reports

- TAC works best when there is ASDE-X like surveillance in the ramp, to identify when the aircraft are going to be available at the spots. However, in the absence of ramp surveillance, actual gate push-back times for each aircraft are needed, along with estimates of ramp taxi time from the gate to spot.
- Flight operator inputs on estimated push-back times for the above flights
- Traffic Management Initiatives (TMI) for relevant flights in the planning bin. These could include Ground Delay Program (GDP) based constraints or weather based constraints.

It should be noted that in case a flight is delayed at the gate beyond t_{pb}^{*}, it will not be given priority over flights that push back on time. In other words, the SPC calculated spot time for flights that meet the gate push-back time is adhered to within a certain bound, and is not changed due to other flights being late in gate push-back. Late gate push-back could result in the loss of the spot release time for the flight, and through the tactical planner the gap is filled by other available flight. The late flight is then accommodated when possible through SCH.

Uncertainties in aircraft movement pose a challenge to generating tactical advisories. This is addressed by recalling SCH periodically and recalculating all the advisories. In the experiments presented in Section IV, SCH was recalled every 10 seconds. For usage in TAC, SCH is configured with a planning window (look ahead time from current time) as well as recall frequency (time gap between successive SCH calls). For preliminary results presented in the later sections, a planning window of 15 minutes and a recall frequency of 10 seconds are used. Thus, every 10 seconds SCH would take a "snapshot" of the airport conditions, including location and speed of both departure and arrival aircraft, and extrapolate these data for the next 15 minutes. Based on this extrapolation, advisories would be generated for the ATCT controllers. However, due to uncertainty in aircraft movement, successive SCH calls could result in frequent changes in the advisories which would make them unusable. To avoid this, a partial advisory freeze is incorporated: for both the local and ground controller, certain subset of immediate advisories are not changed in successive calls of SCH. For example, for the local controller the first three aircraft in the runway usage sequence are frozen, and the rest can change. For the experiments described in the next section, a freeze value of six at the spot and three at the runway are used. Further research is needed to determine the freeze values for different airports.

C. Alterations for Airport with Single Dominant Carrier

The above concept would be applicable to most airports with minor changes in planning window size, planning horizon size and small alterations in the concept to accommodate variations in ramp procedures. A common case where ramp operations would differ is where one airline is the majority carrier and uses the airport as a hub for operations. If a large percentage of traffic is generated by the dominant carrier, the SPC part of SARDA-CDM can be simplified to just one stage instead of two. Airline preferences for gate push-back time for individual aircraft can be inputs to the first stage of SPC, which make the second stage redundant. Moreover, in this case the airline can also give preferences for departure sequence at the runway; this can be given either for a subset or all the departure aircraft in the planning horizon. Also, the mechanism of giving both Δ_{SR} and t_{pb}^{*} could be altered. The reason for providing Δ_{SR} in the multiple airline case was to incentivize timely push back; early push-back would lead to holding as prescribed by Δ_{SR}. For a single airline case, early push-backs do not have an additional competitive value, and thus, instead of providing Δ_{SR} and t_{pb}^{*}, a push-back window could be provided to the airline.

IV. Preliminary Benefits Assessment of SARDA-CDM

A. Simulation Setup

To conduct an initial assessment of the potential benefits, SARDA-CDM was implemented within the Surface Management System (SMS)[12]. SMS was originally developed as a decision support tool to assist ATCT controllers and managers as well as airline operators in managing and controlling airport surface operations[13]. It was modified into a closed-loop real time simulation platform by configuring it to receive aircraft position data generated by the Air Traffic Generator (ATG)[14]. ATG is a high-fidelity, real-time aircraft simulation tool that provides the capability to move the aircraft on the airport surface and generate and display targets of the aircraft. In the closed loop system, ATG sends the aircraft position data to SMS, and SMS sends back the gate release, spot release, runway take-off, crossing etc commands back to ATG, which then executes the commands automatically. SMS gets all the commands from the scheduler (SCH), which is updated every 10 seconds. This system is similar to the one used for human-in-the-loop simulations to test the tactical SARDA tool[4], and now has been augmented to run as a closed loop real-time environment. It should be noted that the SMS-ATG system can still be used as a platform for human-in-the-loop testing, and a version of the SARDA-CDM system is being tested in the human-in-the-loop setup at the NASA Ames Research Center.

The closed loop SMS-ATG system has methods to separate aircraft on the taxiways, which could lead to some uncertainty in aircraft movement. Besides these, there are other sources of uncertainty in aircraft movement as described below:

- The taxi speed of every aircraft can vary from 12 knots to 17 knots.
- When SMS sends ATG the push-back command for an aircraft, the compliance to that command occurs within 10 seconds.
- When SMS sends ATG the spot release command for a departure aircraft, the compliance occurs within 10 seconds.
- Similarly, compliance for runway crossing and take-off commands from SMS to ATG occurs within 10 seconds.

A modified version of the scheduler used in the 2010 SARDA human-in-the-loop experiment[4] was utilized for the simulations presented in this paper. The modifications include consolidation of the previous two solvers into a unified framework. The scheduler takes as input the current snapshot of the airport, aircraft specific parameters, separation constraints, scheduled push-back times and scheduled arrival times for the aircraft in the next 15 minutes.

To test the benefits of the SARDA-CDM concept, a baseline case is formulated that represents current day operations. In baseline, departure push back occurs at the scheduled push-back time, and the aircraft is not metered at the gate or the spot. As soon as the departure aircraft comes to the spot, it is released immediately to the taxiways as long as there was no conflict with taxiing aircraft. In case of conflict, the taxiing aircraft is given priority. The departure aircraft then queues up at the runway and awaits clearance for take-off based on wake-vortex criteria. The runway sequencing (for take-offs and arrival crossings) is based on a simple swapping heuristic and not first-come-first-served; the heuristic is a better representation of what the controllers do today.

To test the potential benefits of the SARDA-CDM concept, a preliminary version was implemented in the SMS-ATG closed loop system. Given the tactical spot release times calculated by the scheduler, the gate push-back times are evaluated based on nominal ramp to spot taxi times. As the spot times were recalculated every 10 seconds, the push-back times were also recalculated. When uncertainty needs to be induced in gate push-back, ATG adds a delay to the calculated push-back times based on the pre-determined uncertainty parameters. For example, an uncertainty of 30s in gate push back implies ATG would add a delay value from a uniform distribution of 0 to 30 seconds. It should be noted that the uncertainty is always positive, i.e. the aircraft never push-back earlier than the SARDA-CDM push-back time. The aim here is to identify the effect of delays in gate push-back on the SARDA-CDM system. Since this is a metering system where aircraft pushing back earlier are placed in holding areas, only the delayed aircraft could adversely affect the system performance. Five levels of uncertainty were tested: 180 seconds, 120 seconds, 60 seconds, 30 seconds and no uncertainty, with the no uncertainty case referred to as “adv” for pure advisory. It should be noted that even in the no uncertainty case, there is the inherent 10 second uncertainty in push-back due to the SMS-ATG system, as described previously.

As in the 2010 SARDA experiment, the simulations for this paper were conducted on the east side of DFW. Figure 2 shows a 90 degrees clockwise rotation of the configuration of the east side of DFW airport used for the simulations.

Two different traffic scenarios are discussed in this paper; scenario 1 and scenario 2. Scenarios were generated such that departure traffic begins at the gates upon activation in the simulation and arrival aircraft appear about 10 nautical miles from the runway threshold. The scenarios are based on 1.5x current day DFW traffic on the east side of the airport. Both the scenarios have 50 departure aircraft and 30 arrival landings over a period of 50 minutes. There were no TMI restrictions in either of the scenarios. For each test condition 10 runs were performed; for example, scenario 1 was run 10 times with 30s uncertainty in gate push-back.

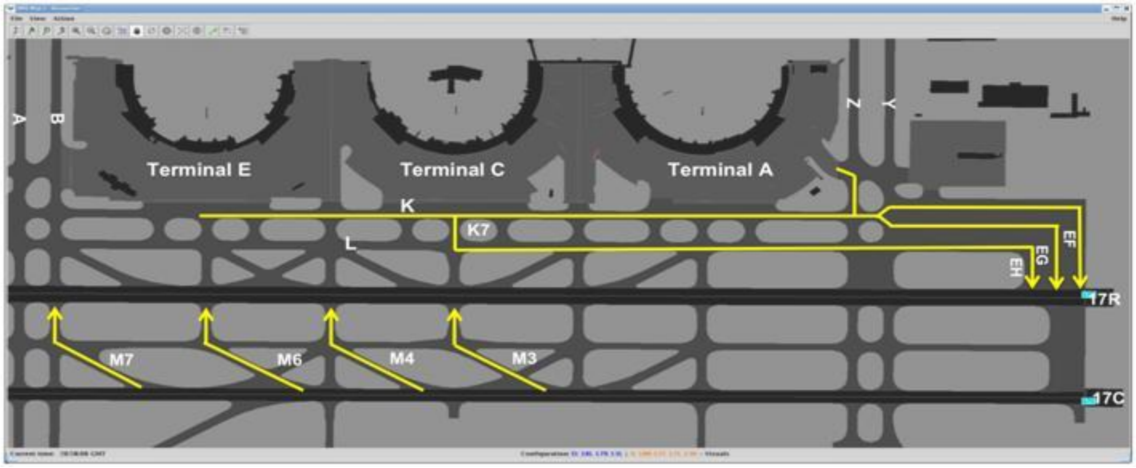
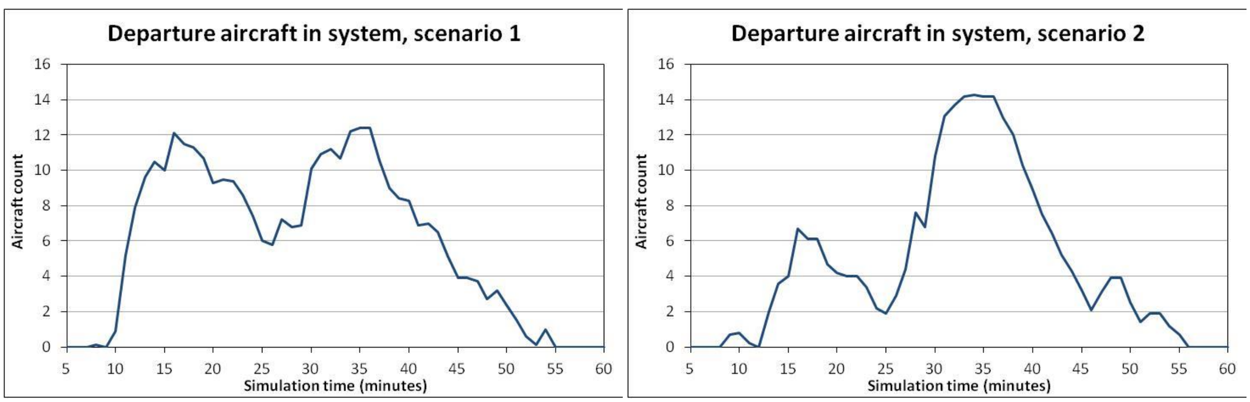


Figure 2: Departure Taxi Routes, Departure Runway Queue, and Runway Crossing Structures of East DFW

Both the scenarios have peaks of departure demand, and the rate of arrival aircraft is almost at the limit of the capacity of one runway. To illustrate the characteristics of the departure demand, the number of aircraft waiting in the system was evaluated for the baseline runs. The number of aircraft waiting in the system is defined as the aircraft that have pushed back but not departed within the unimpeded take-off time from push-back. Figure 3 shows these plots, which show that scenario 1 has two overlapping departure demand peaks, whereas scenario 2 has a very large peak after a smaller peak.



(a) Scenario 1 (b) Scenario 2

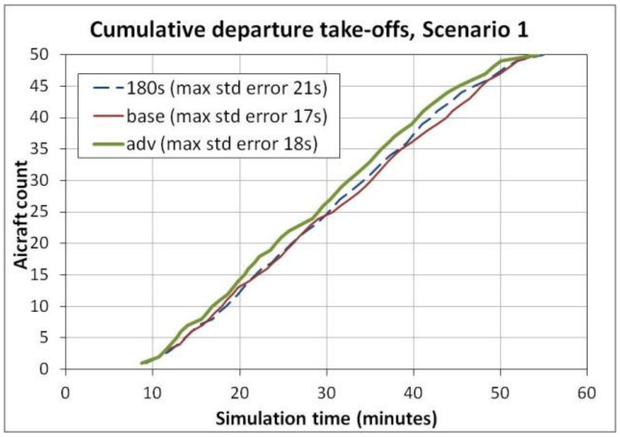
Figure 3: Departure demand peaks in scenario 1 and 2, depicted by number of aircraft waiting in the system

B. Results

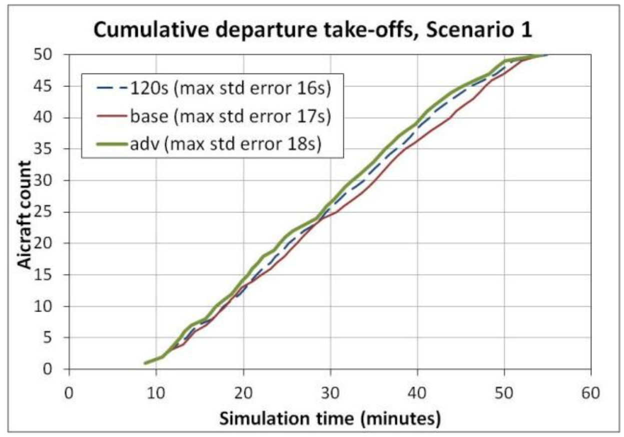
This section presents the results from the simulations described in the previous section. Runway throughput is considered first to evaluate is metering done through SARDA-CDM causes loss in runway usage. Next, benefits in terms of reduction in delay and fuel savings are considered, and the effects on arrival aircraft are evaluated.

1. Runway usage

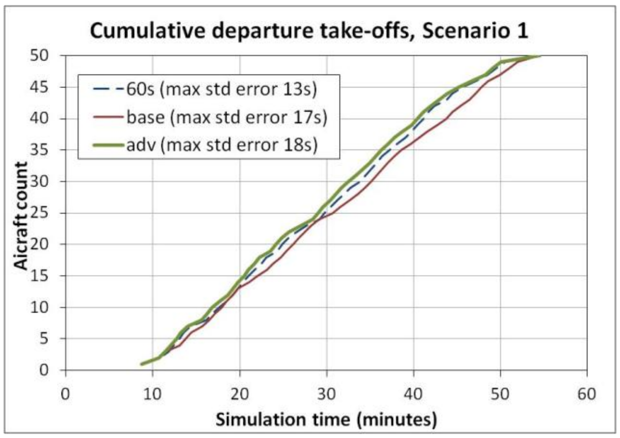
For both scenarios 1 and 2, first runway usage by departures is considered, and then the combined usage with arrivals and departures together is presented. Figure 4 and Figure 5 show the cumulative departure count for scenario 1 and 2 respectively, for the four levels of uncertainty in gate push-back. In each figure, the mean take-off time of each successive departure is plotted across the 10 runs for that particular uncertainty size. Further, to show the variation across the 10 different runs, the maximum of standard error in take off time across 10 runs is given. For every uncertainty window, both the advisory and baseline curves are also given. When the gate uncertainty plot lies above the baseline curve, the runway usage by departure aircraft was as good as in the baseline, if not better.



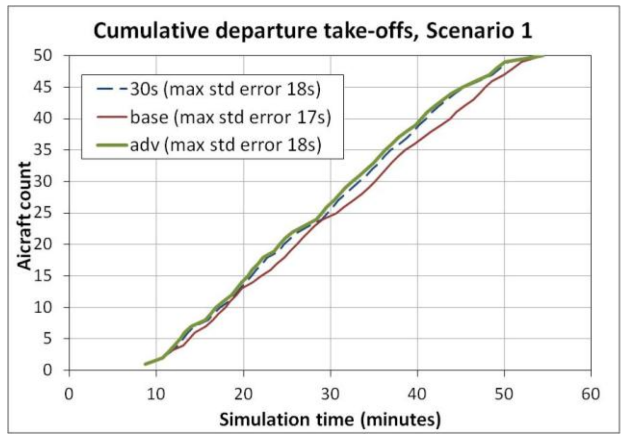
(a) 180s Gate uncertainty



(b) 120s Gate uncertainty

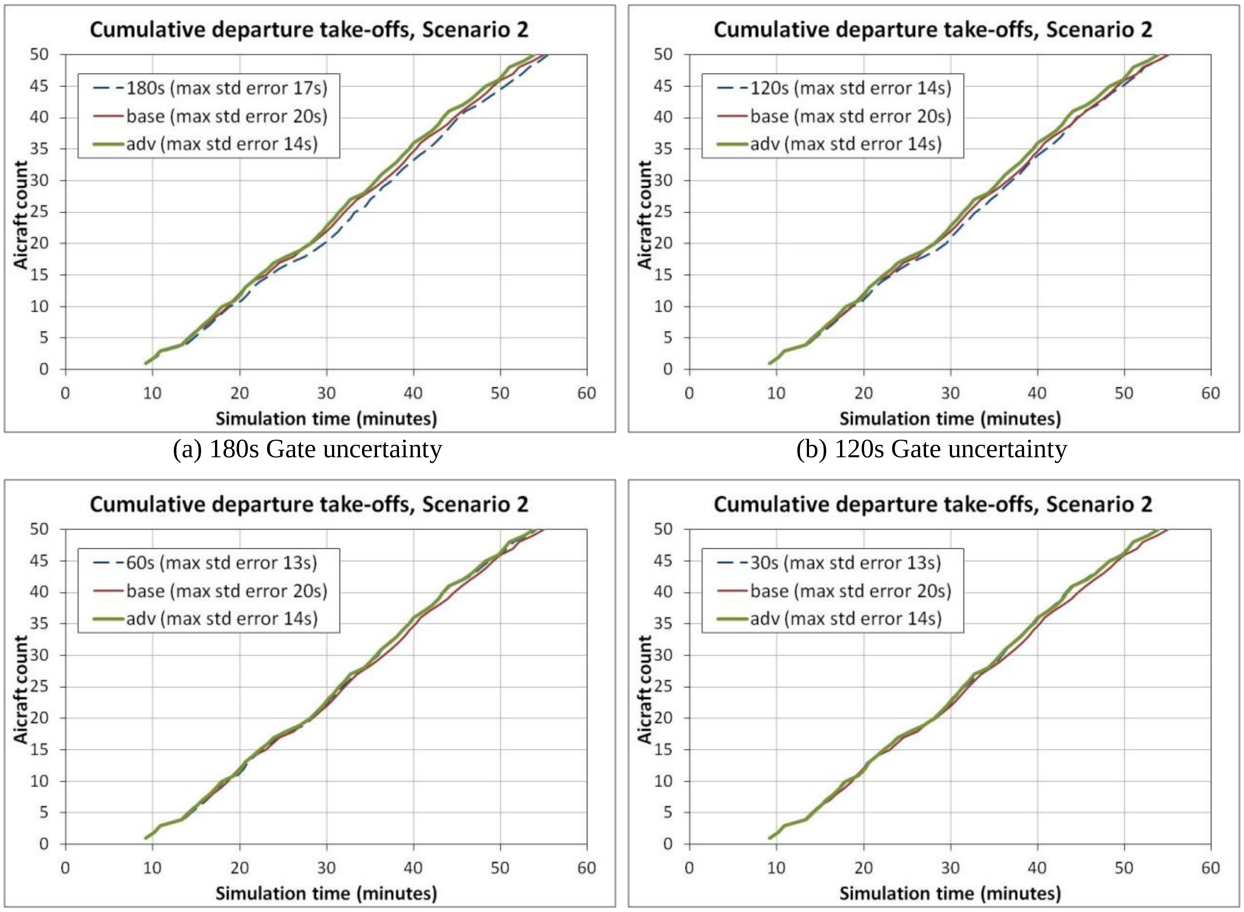


(c) 60s Gate uncertainty



(d) 30s Gate uncertainty

Figure 4: Runway usage for cumulative departure take-offs in scenario 1, averaged over 10 runs each



(a) 180s Gate uncertainty

(b) 120s Gate uncertainty

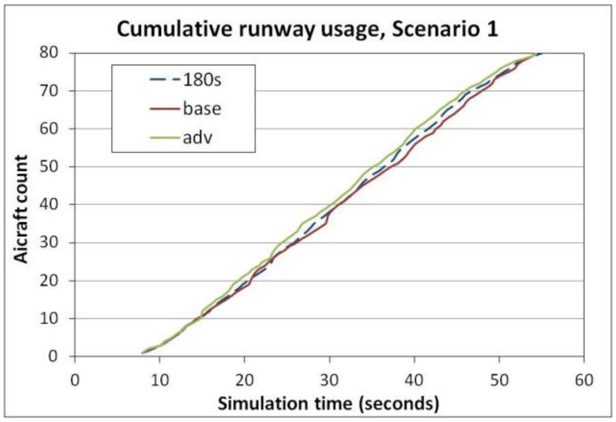
(c) 60s Gate uncertainty

(d) 30s Gate uncertainty

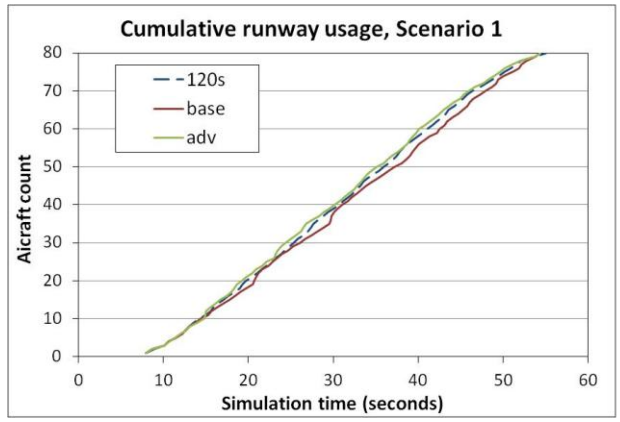
Figure 5: Runway usage for cumulative departure take-offs in scenario 2, averaged over 10 runs each

In scenario 2, the gap between advisory and baseline is slightly less as compared to scenario 1. In both the scenarios, gate uncertainty of 60s has almost no effect. Only in scenario 2 with 180s gate uncertainty the throughput deviates from baseline. Further, all the standard error values are less than 20 seconds, which shows that across the different runs of the same scenario with same uncertainty level, the variation in throughput is small.

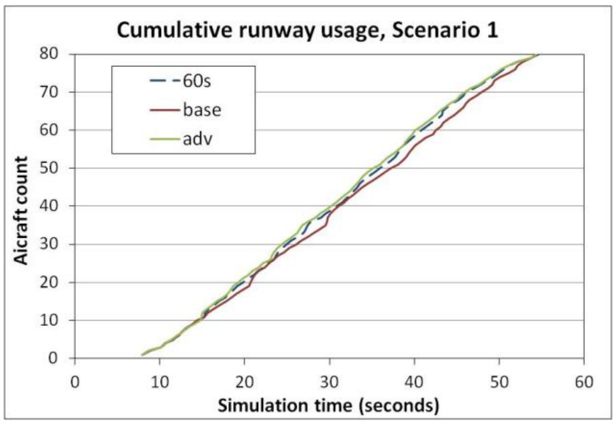
It should be noted that above plots present departure take-offs only. To get the complete picture of runway usage, Figure 6 and Figure 7 show cumulative runway usage including both departure take-offs and arrival crossings. These figures show that even with 180s uncertainty in scenario 2, the loss in runway usage over the baseline is not substantial. In conclusion, there seems to be a small loss in runway usage when aircraft can be about 3 minutes late in meeting SARDA-CDM push back times. However, the scheduler used in these tests is not calibrated to account for uncertainty in gate push-back. With some knowledge of the probability distribution of gate push-back uncertainty, it is possible to calibrate the scheduler to release more aircraft into the departure queue to avoid runway loss at the expense of increased departure queue delay.



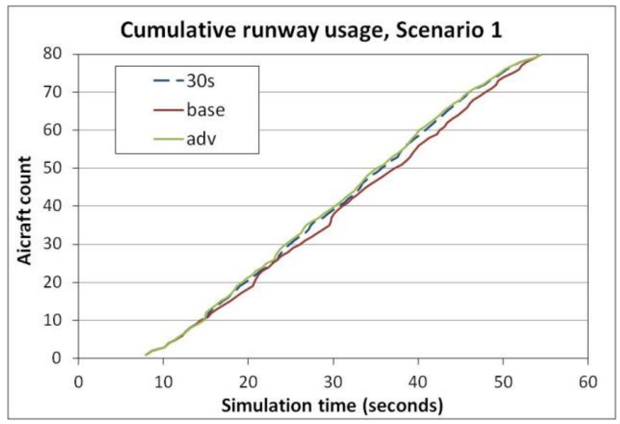
(a) 180s Gate uncertainty



(b) 120s Gate uncertainty

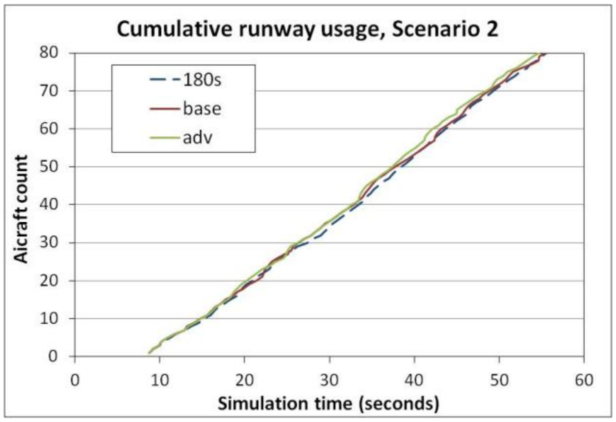


(c) 60s Gate uncertainty

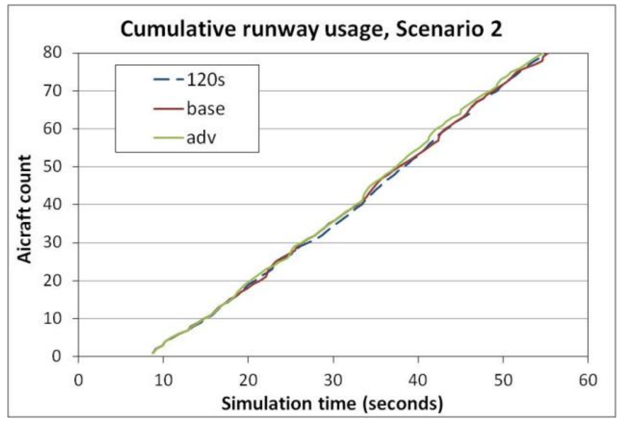


(d) 30s Gate uncertainty

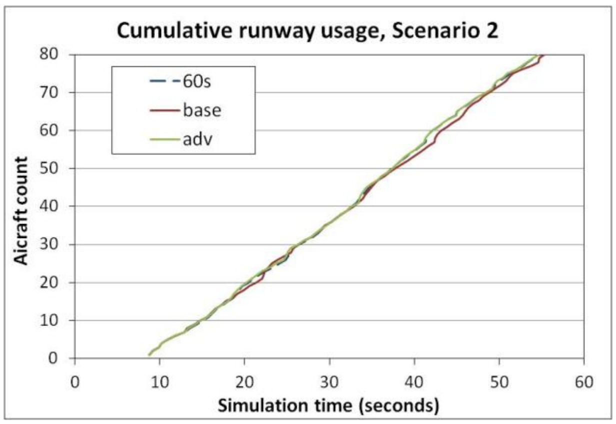
Figure 6: Runway usage by departure and arrival aircraft in scenario 1, averaged over 10 runs each



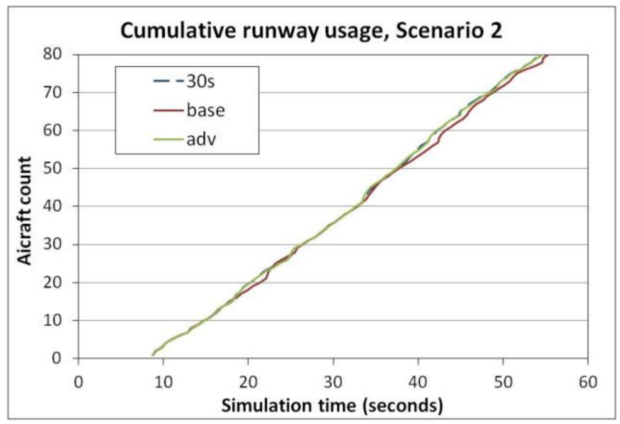
(a) 180s Gate uncertainty



(b) 120s Gate uncertainty



(c) 60s Gate uncertainty



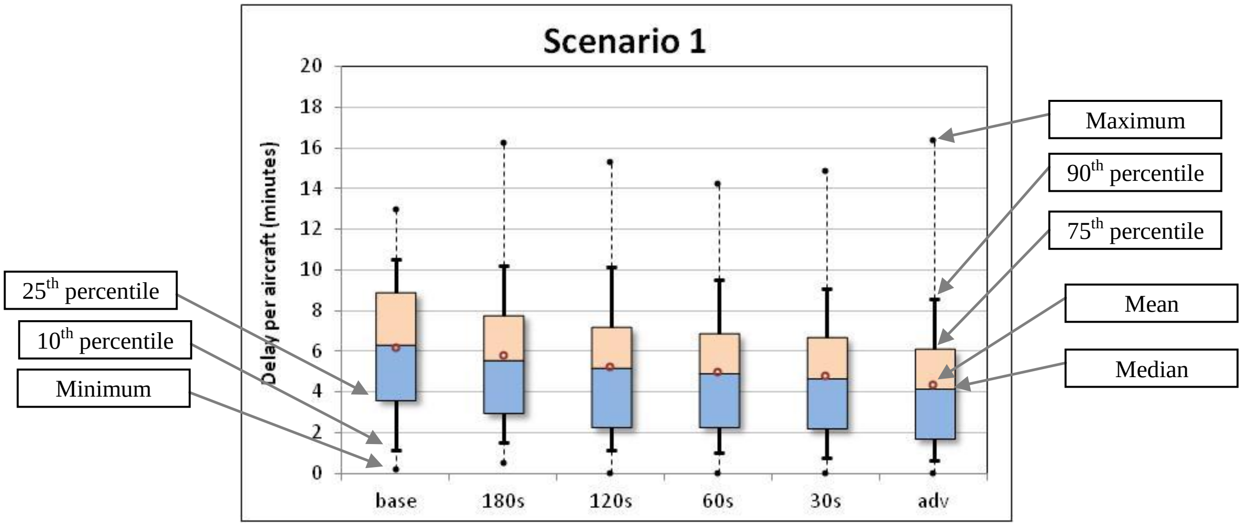
(d) 30s Gate uncertainty

Figure 7: Runway usage by departure and arrival aircraft in scenario 2, averaged over 10 runs each

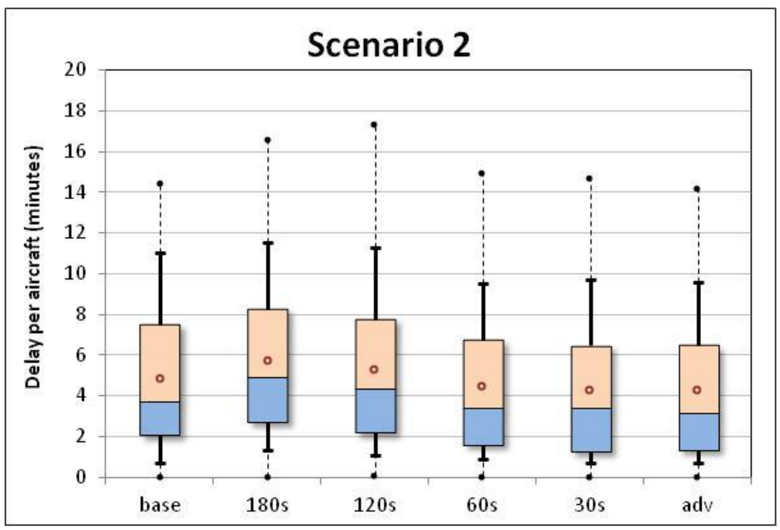
2. SARDA-CDM Benefits

SARDA-CDM aims to move the delay from the taxiways and runway queues to the ramp area by holding at gates or pre-determined holding areas. It is expected that overall delay for all departure aircraft would remain the same between the baseline and SARDA-CDM. Figure 8 shows the schedule delay per aircraft for the different runs of scenario 1 and 2 with different levels of uncertainty as well as for advisory and baseline cases. Schedule delay is defined as delay from the scheduled take off time for departures, which is calculated by adding the unimpeded taxi time to the scheduled gate push-back time. The plots are in the form of box and whisker plots to show the spread of the values across all aircraft, and in Figure 8(a) the various segments of the plots are labeled.

Figure 8 shows there is a slight increase in the schedule delay as the level of uncertainty increases from 30 seconds to 180 seconds when either the mean or the median are considered. Even though the means appear to change, due to the large variation it is doubtful if the change in means is going to be statistically significant. More data to run statistical tests on these numbers is being collected.



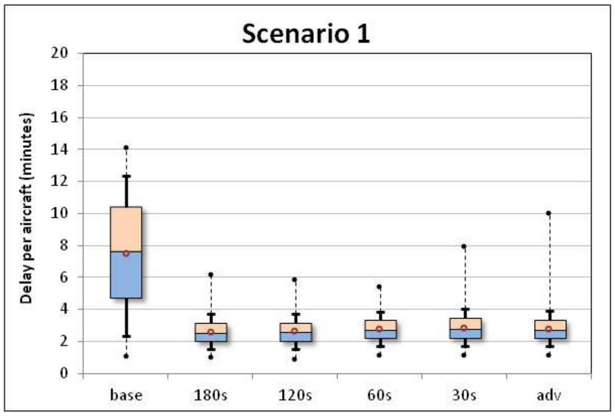
(a) Schedule delay across different runs of scenario 1



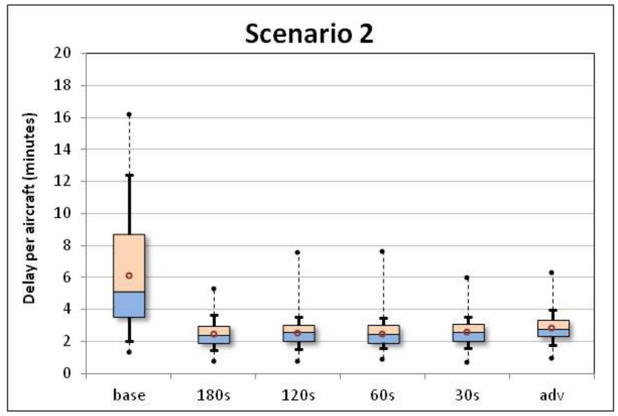
(b) Schedule delay across different runs of scenario 2

Figure 8: Schedule delay for departure aircraft from scenarios 1 and 2

To evaluate the reduction in delay on taxiways due to the use of SARDA-CDM, taxiing delay is evaluated. Taxiing delay is defined as the difference in observed taxi time and unimpeded taxi time; this includes time from actual gate push-back to take off. Figure 9 shows the box and whisker plots for the taxiing delay for both scenario 1 and 2. Even with increasing uncertainty in gate push-back, there is little increase in taxiing delay. The mean taxiing delay decreases from 7.5 minutes in baseline to 3 minutes in SARDA-CDM for 180s gate uncertainty in scenario 1; in scenario 2 this reduction is from 6 minutes to about 2.5 minutes. Further, the variation in taxiing delay is observed to be less with the use of SARDA-CDM.



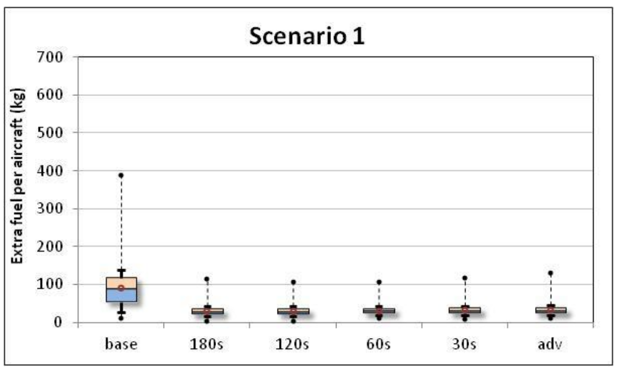
(a) Scenario 1



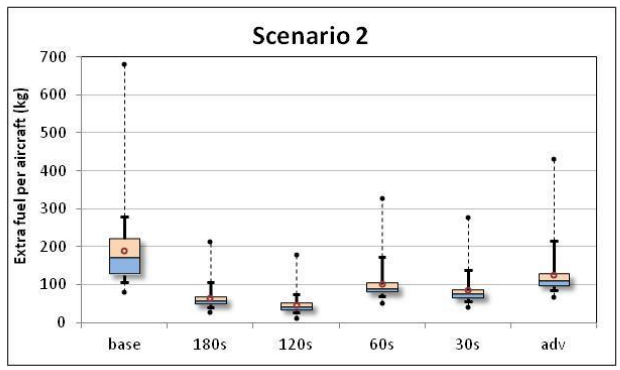
(b) Scenario 2

Figure 9: Taxiing delay for departure aircraft for scenarios 1 and 2

The reduction in taxiing delay as shown in Figure 9 has consequences on fuel consumption also. It is assumed that aircraft engines would only be switched on after push-back. Based on this, extra fuel used is evaluated, which is defined as actual fuel used minus the usage in unimpeded travel over the same route. The method used for evaluating fuel consumption incorporates the effect of stops and acceleration events[15]. Figure 10 gives the results for extra fuel consumption per aircraft for different levels of gate uncertainty as well as the advisory and baseline case. As in taxiing delay, the extra fuel consumed is much less with the use of SARDA-CDM even with 180s push-back uncertainty.



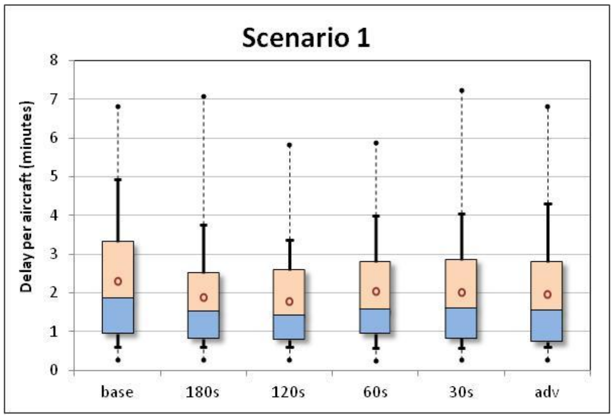
(a) Scenario 1



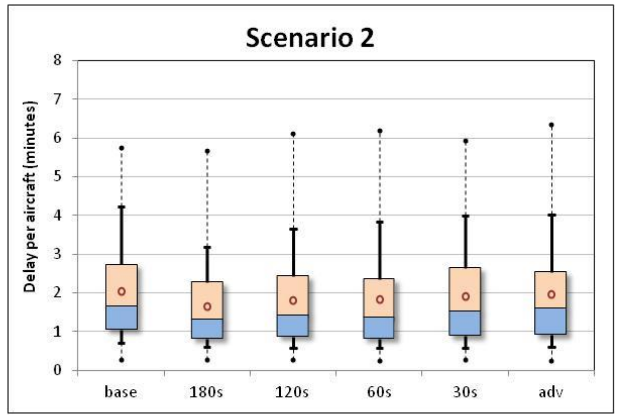
(b) Scenario 2

Figure 10: Extra fuel used by departure aircraft in scenarios 1 and 2

As mentioned before, SARDA-CDM provides tactical runway crossing advisories to the local controller, along with departure take-off sequence advisory. It needs to be checked if the benefits for the departure aircraft are coming at the expense of more delays for the arrival aircraft. For this purpose the total arrival delay is evaluated, defined as the sum of delay in crossing the active runway and delay in taxiing to the spot. As before, delay is calculated as the difference from unimpeded time. Figure 11 shows the arrival delay for both the scenarios for all the levels of gate uncertainty and the baseline case as well. The figure shows very little change in the arrival delay with and without SARDA-CDM.



(a) Scenario 1



(b) Scenario 2

Figure 11: Arrival delay in crossing and taxiing in scenarios 1 and 2

V. Conclusions

This paper describes the SARDA-CDM concept, which includes a strategic planning component for surface CDM, as well as a tactical advisory tool for the Air Traffic Control Tower. The concept meters the departure aircraft in the ramp or holding areas to increase the efficiency of surface operations. Preliminary evaluation in a real-time automated simulation environment indicates benefits in terms of reduction in taxiing delay and fuel consumption. These initial results also indicate that the implementation is robust to 2 minutes delay in gate push-back generated by the strategic CDM component.

In the future, more tests of the system over a wide range of scenarios with different traffic loads would be conducted. Further, larger planning horizons for the strategic component would be explored, and the effect of push-back uncertainty in such cases would be evaluated. The potential benefits of the SARDA-CDM concept towards increasing predictability in surface operations will also be evaluated. Lastly, the concept is by no means complete. Alterations would have to be made based on the user inputs and airport specific criteria (for example: highly constrained ramp area, a single dominant carrier and other factors). The development of the interfaces for the stakeholders is ongoing research.

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