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Airport Surface Traffic Management Decision Support: Perspectives Based on Tower Flight Data Manager Prototype

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16. Abstract

This report describes accomplishments and insights gathered during the development of decision support tools as part of the Terminal Flight Data Manager (TFDM) program. This work was performed by MIT Lincoln Laboratory and sponsored by the Federal Aviation Administration (FAA). The TFDM program integrated flight data, aircraft surveillance, information on weather and traffic flow constraints, and other data required to optimize airport conguration and arrival/departure management functions. The prototype has been evaluated in both human-in-the-loop simulations, and during operational tests at Dallas/Fort Worth (DFW) International Airport.

In parallel, the Laboratory estimated future national operational benefits for TFDM decision support functions, using analysis and performance data gathered from major airports in the US. This analysis indicates that the greatest potential operational benefits would come from decision support tools that facilitate: i) managing runway queues and sequences, ii) tactical management of flight routes and times, impacted by weather and traffic constraints, and iii) managing airport configuration changes. Evaluation of TFDM prototype decision support functions in each of these areas provided valuable insights relative to the maturity of current capabilities and research needed to close performance gaps.

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EXECUTIVE SUMMARY

This report describes accomplishments and insights gathered during the development of decision support tools as part of the Terminal Flight Data Manager (TFDM) program. This work was performed by MIT Lincoln Laboratory and sponsored by the Federal Aviation Administration (FAA). The TFDM program integrated flight data, aircraft surveillance, information on weather and traffic flow constraints, and other data required to optimize airport configuration and arrival/departure management functions. The prototype has been evaluated in both human-in-the-loop simulations, and during operational tests at Dallas/Fort Worth (DFW) International Airport.

In parallel, the Laboratory estimated future national operational benefits for TFDM decision support functions, using analysis and performance data gathered from major airports in the US. This analysis indicates that the greatest potential operational benefit would come from decision support tools that facilitate: i) managing runway queues and sequences, ii) tactical management of flight routes and times, impacted by weather and traffic constraints, and iii) managing airport configuration changes. Evaluation of TFDM prototype decision support functions in each of these areas provided valuable insights relative to the maturity of current capabilities and research needed to close performance gaps.

Figure 1 summarizes our assessment of the maturity of decision support functions in each of the key areas as observed through the development of the TFDM prototype. Note that a number of decision support functions cooperate in delivery of benefits to a key area – for instance runway assignment, taxi routing, scheduling and sequencing, and departure metering interoperate to facilitate management of active runway queues and sequences.

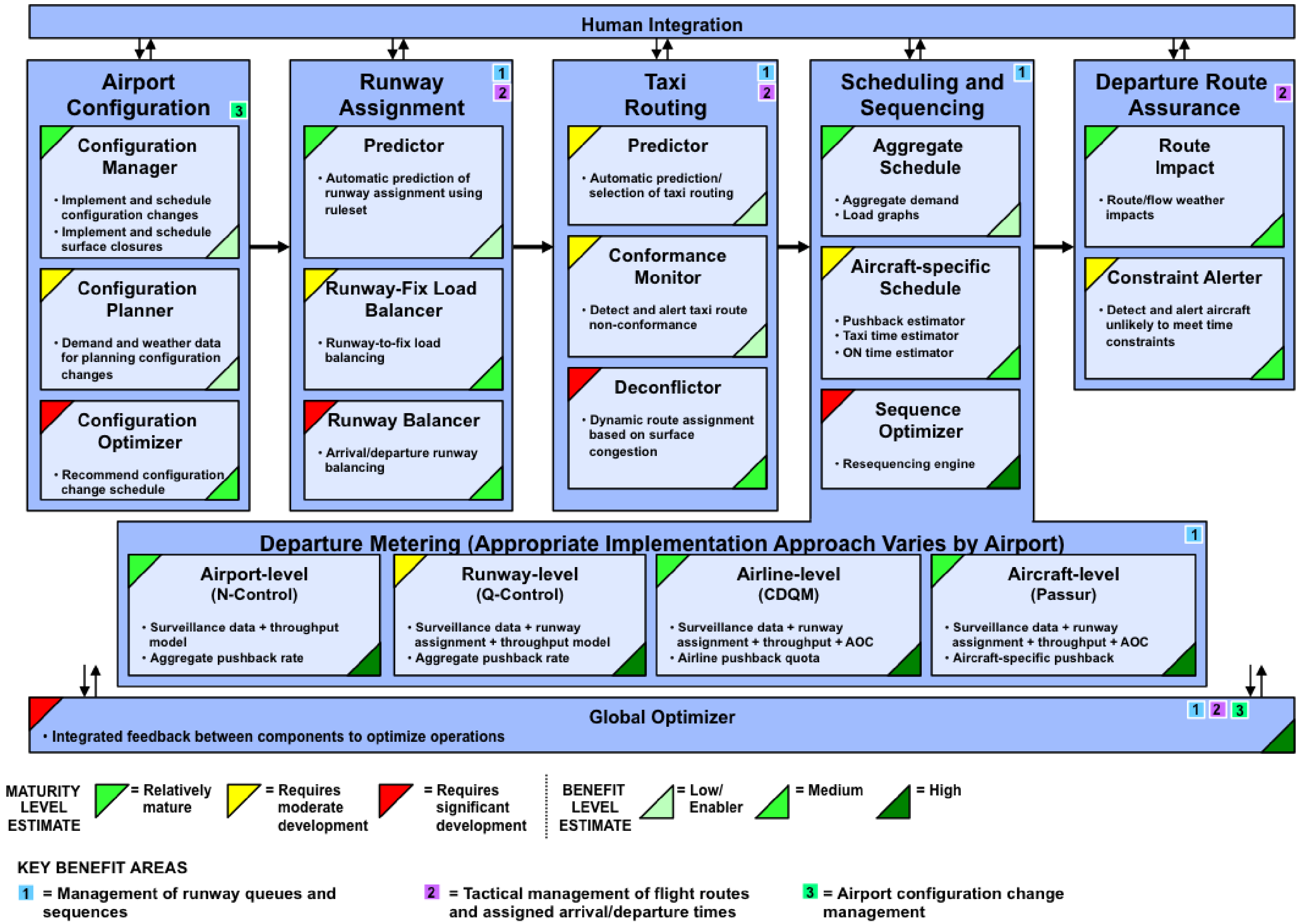

Figure 1: DST capability evolution with maturity and benefits estimates.

In the following we summarize findings that highlight gaps in maturity for each of the key benefit areas. The summary findings are supplemented with specific recommendations for follow-on efforts aimed at closing the gaps.

Management of runway queues and sequences: The complexity of surface operation, as well as uncertainties in traffic and weather constraints, are a challenge to predicting queue occupancy and runway sequences. Improving queue and sequence decision support for management during convective weather constraints is particularly important given the high degree of surface management inefficiency (e.g., long taxi out delays) associated with such events. The following list provides findings and corresponding recommended actions that are needed for maturing decision support capabilities to a level appropriate for initial operational use:

FINDING 1.1: Decision support algorithms depend on parameters that must be customized to each airport site (e.g., number of separate queues available at each runway, use of intersection departures, gates/terminal preferred by airline, presence of runway crossings). This process requires collecting and analyzing operational data over long time periods so that the airport operations can be properly characterized. The decision support algorithms and displays must then be tailored to that operational environment. To assist in this process, generalized adaptation processes and software need to be developed. Until such adaptation processes and tools are in place, the cost of developing and validating unique adaptation software for separate sites will be high.

Recommendation 1.1a: A common representation of airport adaptation parameters should be developed that can allow decision support algorithms to be generalized for multiple sites. Requirements and processes for collecting and applying operational data to inform parameter tuning need to be developed. Additionally, methods and criteria for validating the accuracy of site-adapted parameters need to be defined.

FINDING 1.2: Metering and sequencing decision support algorithms require accurate predictions of aircraft movement in order to provide guidance during constraints such as Expected Departure Clearance Time (EDCT) and to form efficient sequences which satisfy separation constraints. As a result, algorithms require off-time estimate accuracies on the order of one minute over a time horizon of approximately thirty minutes. The existing algorithms are unable to achieve the required accuracy due to the lack of visibility into the status of aircraft at the gate or in the ramp area and a lack of consideration for auxiliary parameters such as type of aircraft or aircraft operator which have been shown to be important in predicting taxi time.

Recommendation 1.2a: Further study and maturation is needed to improve algorithms for predicting taxi time, queue occupancy time, and time spent in ramp/spot. This requires developing more comprehensive timing models. Machine Learning techniques hold the promise of enabling more robust aircraft movement timing estimates. Successful algorithms are expected to employ a richer set of input parameters, can model the impact of auxiliary variables (beyond explanatory variables such as distance or location), and remain robust if some inputs become unavailable.

Recommendation 1.2b: Similarly further study and maturation should be pursued into algorithms for predicting arrival times by incorporating complementary inputs including: surveillance, estimates from Traffic Management Advisor (TMA) (and TBFM in the future), historical data, as well as current and forecasted weather conditions. This would assist in enhancing efficient of arrivals (along with departures).

FINDING 1.3: Preliminary analysis has shown that diversity and evolution of the fleet mix at an airport provides an opportunity for significant benefit from optimizing departure and arrival sequences by taking advantage of differences in separation requirements for different weight classes. Given a significant diversity of aircraft, delay savings can range approximately upto four hours a day.

Recommendation 1.3a: Further study is needed to determine sites that would benefit from automation-based sequence recommendations, and there is a need for maturing algorithms for recommending runway sequences that are robust to uncertainty in forecasted demand. A range of sequence optimization methods is possible, but the particular operational environments best suited to each approach needs to be determined.

FINDING 1.4: Emissions and fuel burn can be significantly reduced by employing time based departure metering approaches (e.g., metering push-backs). For instance, the application of the N-Control metering method tested at BOS has shown significant benefit in reducing emissions and fuel burn. The benefits analysis performed for BOS corroborate the results of operational tests of the N-Control approach. Analysis also shows that the realization of benefits is sensitive to the proper selection of queue threshold parameters.

Recommendation 1.4a: Perform a rigorous study of benefits provided by metering approaches with varying fidelity of control (e.g., N-control (or Q-control), Collaborative Departure Queue Management (CDQM), and Collaborative Departure Scheduling (CDS)). This study should also articulate the information availability and quality requirements needed to enable each metering approach.

Recommendation 1.4b: Investments should be made on maturing algorithms for predicting queue sizes, developing adaptation analysis for determining the appropriate threshold queue settings for efficient metering, and simulation of algorithms to assess their performance.

FINDING 1.5: The accuracy, availability, and relative importance of input parameters used by prediction algorithms can vary from site to site, and over time. During the prototype development process it was found that this is also the case for much of the data, derived from the national airspace system or other external sources, that is critical for decision support tools (such as surveillance, traffic management predictions, weather forecasts, and airline operations data).

Recommendation 1.5a: Algorithms should be tested via simulation and tuned to be robust under varying accuracy and availability of input data.

FINDING 1.6: Metering in convective weather is limited by uncertainty of forecasts. Uncertainty in weather impacts the prediction of achievable throughput and available slots for departures. As a result, this can interfere with the ability to fully realize benefits.

Recommendation 1.6a: A more explicit analysis of metering under convective weather scenarios is needed, as well as the development of strategies for coping with uncertainty, and algorithms whose predictions are robust under uncertainty.

Progress on these steps can be initiated by leveraging algorithms and concepts developed during the TFDM prototyping effort, as well as other research efforts such as NASA's Spot Runway Departure Advisor (SARDA) and System Oriented Runway Management (SORM). Algorithms and techniques from these research efforts (such as improved taxi-time and queue occupancy prediction models) should be further integrated into a surface decision support system and matured through field or simulation testing for a diverse set of airports. These efforts can also leverage the past and ongoing efforts by N-control, Collaborative Departure Queue Management (CDQM) and Collaborative Departure Scheduling (CDS) in maturing departure metering concepts.

<u>*Tactical management of flight routes and times*</u>: Inefficiencies in this area typically arise from un-

certainties in weather, airspace traffic demand, traffic management initiatives, and complexity in coordination of flight routes and times with other facilities. The findings and recommended follow-on activities for maturing concepts in this area are:

FINDING 2.1:	Improvements in tactical departure management are expected to provide a significant benefit. However, a detailed and sound concept of operations and functional allocation for collaborative management between surface automation, TBFM, TFMS, and airline flight operations has not been adequately defined.
Recommendation 2.1a:	A concept of operations document which clearly describes the information exchange between the different automation systems, and the associated functional upgrades should be developed, driven by case based evaluation of operational issues.
FINDING 2.2:	Validation and refinement of collaborative decision support tools for tactical management of departures (and arrivals) within the context of emerging NextGen automation platforms has yet to be performed.
Recommendation 2.2a:	Investment is needed in prototyping of collaborative departure route and time management of flights with TBFM, TFMS, airline operations, and surface automation.
FINDING 2.3:	Both TFDM and Integrated Departure Route Planning (IDRP) trials have shown that accurate off-time estimates and calibrating their level of uncertainty are important for selecting between re-route alternatives. Current timing accuracies are not sufficient to extract significant operational benefits.
Recommendation 2.3a:	Improved prediction algorithms mentioned above should be integrated into a departure management decision support tool.
Recommendation 2.3b:	Improved off-time predictions should be shared with TBFM and TFMS in order to develop consistent estimates of departure demand generated by the airport surface, and accurate capacity estimates should flow from TBFM and TFMS to surface automation to assist with mediating the flow of departures. Surface automation algorithms would need to be upgraded to exploit the incoming capacity information (for instance in the form of meter lists relative to flow constraint areas) in order appropriately select amongst departure route (and runway) options.

FINDING 2.4: Suitable operational user interfaces for tactical departure management situated at collaborating facilities have yet to be developed. This is due to the unavailability of a detailed concept of operations, and segmented prototyping efforts in this area. At the moment it is not clear how information related to impacts of traffic and weather constraints should be presented to controllers at different facilities in a consistent fashion, and how the automation ought to facilitate decision interactions towards a mitigation (e.g., coordinated re-route of multiple impacted aircraft).

Recommendation 2.4a: Methodical controller evaluations of user interfaces should be coupled to prototyping and high-fidelity simulation efforts for maturing the content and format of information/options presented to controllers.

There is a need to focus on interface (exchanges with time based metering, traffic flow management, and airlines) and algorithm development for collaborative management to efficiently move flights to/from the surface. These design efforts should be coupled with capabilities for the demonstration and maturation of concepts that involve multi-facility (or multi-automation system) coordination of departure flight routes and time slots under tactical operations. The FAA has made some initial investments in this area which can be leveraged.

Managing airport configuration changes: A major factor in managing airport configuration change is the ability to accurately forecast terminal area winds. There are other factors which influence the selected aiport configuration, such as community noise considerations and managing traffic volume. There are also complexities of coordinating the airport configuration with operations at other airports in a metroplex. There has been some research into approaches for configuration management while considering the effects of weather, traffic and noise constraints. However a committed effort is needed to translate this research into tools that can be employed in an operational environment. Significant benefits can be had by initially focusing on maturing terminal wind forecasts. Common access to these forecasts and the corresponding predicted state of surface operations amongst coordinating facilities is important for effective decision making. The following findings and the associated actions are recommended to mature capabilities in this area:

FINDING 3.1:	Inefficiencies in airport configuration change management typically result from inaccurate or inadequate information on terminal area winds. Preliminary analysis suggests that optimizing airport configuration at BOS could potentially result in four to eight hours of daily delay savings. In order to make effective decisions concerning airport configuration, wind forecasts out to two hours with approximately five minute resolution are needed. It is also important to measure the uncertainty associated with the forecast. Existing wind forecasts (e.g., TAF, ITWS wind shift product) are not able to provide the time resolution and accuracy needed. Furthermore, airport configuration management algorithms that integrate these data and compare impacts (e.g., excess delay) amongst a set of feasible configurations are also lacking. There is also a need to validate forecasts by comparison with actual wind observations.
Recommendation 3.1a:	Initial work on generating wind forecasts based on state-of-the-art weather products, such as the ITWS gridded terminal winds product and the High Resolution Rapid Refresh (HRRR), should be matured and integrated into an airport configuration management decision support tool. This effort is aimed at satisfying the forecast duration (up to two hours) and update resolution (five minutes) that are needed for improved decision making. The generated wind forecasts should be validated with actual wind observations.
Recommendation 3.1b:	Further investment is needed to develop algorithms that can integrate the wind forecasts, airport arrival/demand forecasts, and configuration changeover penalty to determine the delay performance of feasible configurations, as well as suggest an appropriate time to change configurations.
Recommendation 3.1c:	The achievable arrival/departure capacity of an airport for different configurations is a function of the particular airport and is typically determined from analysis of historical data. Work is needed to analyze historical data for a small set of key airports in order to tune the functionality of airport configuration management algorithms and to establish adaptation parameters.

FINDING 3.2:	Airport configuration change decisions are workload intensive due to necessary coordination between multiple facilities and stakeholders. These decisions can be assisted by improved situational awareness on the impact to operations at nearby facilities (e.g., airports in a metroplex)
Recommendation 3.2a:	Develop a prototype to test and refine multi-facility collaborative airport configuration management concepts.

Recommendation 3.2b: Refine information exchange concepts for providing situational awareness and contextual information to collaborating facilities to assist decisions.

> There is again significant effort needed to mature research in airport configuration management for use by operational decision support tools. However, there are activities that can be leveraged such as the System Oriented Runway Management (SORM) at NASA, as well as the initial wind prediction algorithms developed under the TFDM prototyping effort. The development of airport configuration management techniques that consider a majority of key constraints, such as wind, noise, traffic demand, and metroplex operations are still in early stage of research. Further investment into maturing this research and its translation to operational tools is warranted.

Further work developing decision support capabilities should be both data-driven and validated to the level suitable for operational use. This leads to several general recommendations that cut across those presented above:

- Establish a technically informed roadmap for incremental development of key decision support functions.
- Perform rigorous benefits studies using a mix of fast-time simulations, human-in-the-loop studies, and field data collection exercises.
- Conduct prototyping activities designed to validate the readiness of decision support algorithms and concepts of use.

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1. INTRODUCTION

1.1 OVERVIEW

Air traffic control towers (ATCTs) are responsible for the safe and efficient handling of aircraft on the surface and in the immediate vicinity of airports. In current towers, many systems (over 80 in large facilities) are in place to support tower operations, such as surveillance, communications, weather information and flight data systems. Many of these systems are independent and the controllers need to manually or cognitively integrate the information as required by the operational circumstances. Many of these originated in single-facility initiatives and have been tailored to meet requirements of a particular site's traffic conditions, airspace configuration, and aircraft operators. These individual systems often exhibit overlap in functionality, and are not designed to be readily expandable to new requirements. There are significant technical and economical challenges in attempting to couple such systems into an integrated whole in order to adequately support the evolving demand in surface operations. Although the legacy systems provide useful individual capabilities, there remains a need for an integrated tower automation and decision support system that is designed from the start to evolve with the requirements for the Next Generation Air Transportation System (NextGen) systems portfolio.

The need for enhanced automation and decision support capabilities in the tower is also driven by the expected increase in demand on the air transportation system. As demand increases in the future, there is a need to support air traffic management objectives for efficiency and performance enhancements, such as those envisioned under the NextGen [1] and Single European Sky ATM Research (SESAR) [2] programs. Improving airport operations is a key element given the finite airport resources and the fundamental role that ground operations play in implementing gate-to-gate trajectory management techniques. Airport system efficiency and performance gains may be achieved by a variety of means. For example, as the volume and complexity of traffic increases over time, controller workload can be managed by providing new automation. As new automation is introduced, there is a need to consolidate diverse tower automation systems into fewer systems, displays, and keyboards (which in turn provides cost efficiency gains). The integrated tower automation systems rely on the provision of electronic data exchange which then affords numerous opportunities for system improvements. Information sharing between different stakeholders (e.g., ATC, airline, airport operator) allows for Collaborative Decision Making (CDM) for sharing of preferences, better demand predictions and more strategic decision-making [3]. Integrated electronic processing of flight, surveillance and weather data allow more effective creation and management of traffic management initiatives. And decision support tools (DSTs) can be created to take advantage of integrated information environments to improve the execution of air traffic control procedures.

Decision support tools can assist controllers in managing the aggregate complexity and uncertainty arising from evolving traffic demand, traffic constraints, weather constraints, and airline operations. Analyses suggest that, generally, traffic management functions which are complex and sensitive to uncertainties, are also the ones which are associated with the highest potential for benefits with assistance of decision support tools. The Tower Flight Data Manager (TFDM) shortfall analysis [4] identified the highest benefit potential traffic management functions as: i) managing runway queues and sequences, ii) tactical management of flight routes and departure times, impacted by weather and traffic constraints, and iii) managing airport configuration changes . It is useful to consider the types of uncertainties or complexities that influence operational efficiency of these traffic management functions, and how such influences can be mitigated.

The primary high benefit potential function is the management of runway queues and sequences. Effective management of departure queues can result in improved throughput, reduced delays, and reduced fuel burn/emissions. The management of departure queues can however be a complex task. This task involves ensuring that each aircraft enters the desired departure queue at the appropriate time and in the appropriate order. The appropriate entry time and placement in the queue are influenced by dynamic constraints arising from surface traffic congestion, en route traffic constraints, uncertainties in push-back times, flexible runway use (e.g., intersection departures), uncertainties about availability of time slot in the overhead stream, and the need for maintaining safe separation between aircraft. In addition to these constraints, the airport surface plan also imposes constraints on where queues may form, and how aircraft must taxi in order to join their respective queues. For instance, some airports may allow multiple queues to feed a single runway, and there may also be opportunities for queuing in the ramp and other designated areas, while other airports may be space constrained and support only single runway queues. Algorithmic solutions to assist departure queue management must therefore: i) accurately model and forecast surface traffic dynamics, ii) consider multi-queue environments, iii) account for dynamics in surface, terminal and en route traffic constraints, iv) account for dynamics in airline flight operations, and v) provide means for controlling queue occupancy. The accuracy of techniques for modeling surface dynamics, as demonstrated by trial or fielded systems to date, is currently not adequate for operational decision making. Later in this report we discuss candidate techniques which have shown promise in fast-time simulation case studies, but require further maturation for operational use. Preliminary work has begun to consider robustness of algorithms in the presence of variability in driving constraints from surface, terminal and en route. The accommodation of multi-queue environments (which includes intersection departures) is a topic which has not received adequate attention. Apart from algorithmic considerations, techniques for accommodating multiple queues are expected to depend significantly on the plan and procedures employed at the specific airport. The ability to account for the decisions of airline operations, such as gate push-backs, relies on communications with airline systems where possible. It is unlikely there would be uniformity in the availability and relative accuracy of information acquired from airline operation systems. As a result, algorithmic approaches that are robust to such non-uniformities are desirable.

The ability to control the size of runway (or other) departure queues is viewed as a critical aspect of queue management. Approaches based on departure metering from the gate (or other positions) have shown promise in operational trials, including highly successful N-Control trials conducted by MIT at Boston Logan Airport (BOS) [5], Collaborative Departure Queue Management (CDQM) field tests at Memphis International Airport [6], and Passur's departure metering program at John F. Kennedy Airport [7]. The TFDM prototype system discussed in this report has implemented one such approach, which was an adaptation of the approach developed for Boston. However due to the relative immaturity of accurate surface traffic modeling and forecasting capabilities, this approach has not been completely tested and tuned. Since application of metering solutions also has a significant dependence on airport site plan and procedures, additional tests (with accurate surface models) are needed at a diverse set of airport sites.

The second high benefit potential function is the tactical management of flight departure routes and times, which are impacted by weather or traffic constraints. Uncertainty associated with convective weather events can diminish the time horizon over which impact to planned flight routes can be predicted. The ability for mitigating the impact of weather or traffic constraints on flights expecting to depart within 30 minutes requires improvements in weather and traffic predictions. These predictions need to be translated into an assessment of impact on flights. There is also the need for quick access to recommendations that would assist in mitigating the impact. And finally, the selection of an agreeable course of action requires rapid coordination between facilities, and notifications sent to aircraft flight decks. There have been prototyping efforts (leading to field evaluations) which have demonstrated component capabilities needed for developing a collaborative departure routing function. The Route Availability and Planning Tool (RAPT) [8] has demonstrated the value (through improved operational efficiencies) of providing forecasts about weather impact, as well as sharing the forecasts amongst collaborating air traffic facilities. In the case of traffic constraints, trials of Departure Flow Manager (DFM) [9] have demonstrated the utility of coordinated departure management between tower, terminal, and en route facilities while controlled departure times and approval requests (APREQs) are in effect. The Integrated Departure Route Planner (IDRP) [10] effort has conducted field evaluations of coupling weather impact forecasts (using RAPT) with flight data, and alternate flight routings. The integration of these concept decision automation systems (or their successors operational systems), with surface decision suppport capabilities provides the opportunity for developing an initial tactical departure route management capability. The effectiveness of this capability does depend on maturing surface traffic modeling and forecasting capabilities. However there remains a significant challenge here in the integration of multiple systems, harmonizing exchange of forecast data between these systems, and tuning their underlying algorithms for coordinated operation.

In the case of airport configuration management (the third highest benefit potential function), complexity can arise from the need to coordinate configuration change operations with adjacent airports, Terminal Radar Approach Control (TRACON), Air Route Traffic Control Center (ARTCC), and the Command Center. A coordinated decision on airport configuration change typically relies upon an expected shift in terminal and surface wind conditions. The coordination of airport configuration can benefit from collaborative automation tools, as well as accurate forecasts about terminal winds and airport traffic demand. The decisions of how to best balance between servicing arrival and departure demand is impacted by expected traffic and weather constraints, along with the runway and fix constraints. For instance the selection of an airport acceptance rate (for arrivals) can be viewed as an outcome of selecting a feasible airport configuration. Then based on the underlying configuration and other resource constraints (such as runway to fix mapping), the most suitable arrival/departure rate operating point to maximize traffic throughput can be selected. The development of an operationally useful airport configuration management tool then relies upon the maturity of: i) effective tools/interfaces for collaborative coordination of configuration change, ii) accurate forecasts of terminal area winds, and iii) accurate models of achievable runway utilization for arrivals and departures. The level of these capabilities is not yet adequate for an operational system. We recommend that further effort towards improving airport specific throughput models, supplemented with field evaluations or high fidelity simulations, would assist in maturing decision support capabilities for airport configuration management.

1.2 TFDM AND ITS CONTEXT WITHIN WIDER ATC AUTOMATION

This report primarily focuses on the decision support functions that are envisioned to be part of an integrated tower automation system, named the Tower Flight Data Manager (also referred at times as Terminal Flight Data Manager). The Tower Flight Data Manager prototype development was sponsored by the Federal Aviation Administration (FAA) in order to mature and validate concepts for an integrated tower automation and decision support platform that would enhance the efficiency of airport surface operations [11]. In order to provide a context for how decision support functions fit into the TFDM architecture, we begin with a discussion of the recommended architecture. At a high level, this architecture is illustrated in Figure 2. As implemented, our prototype

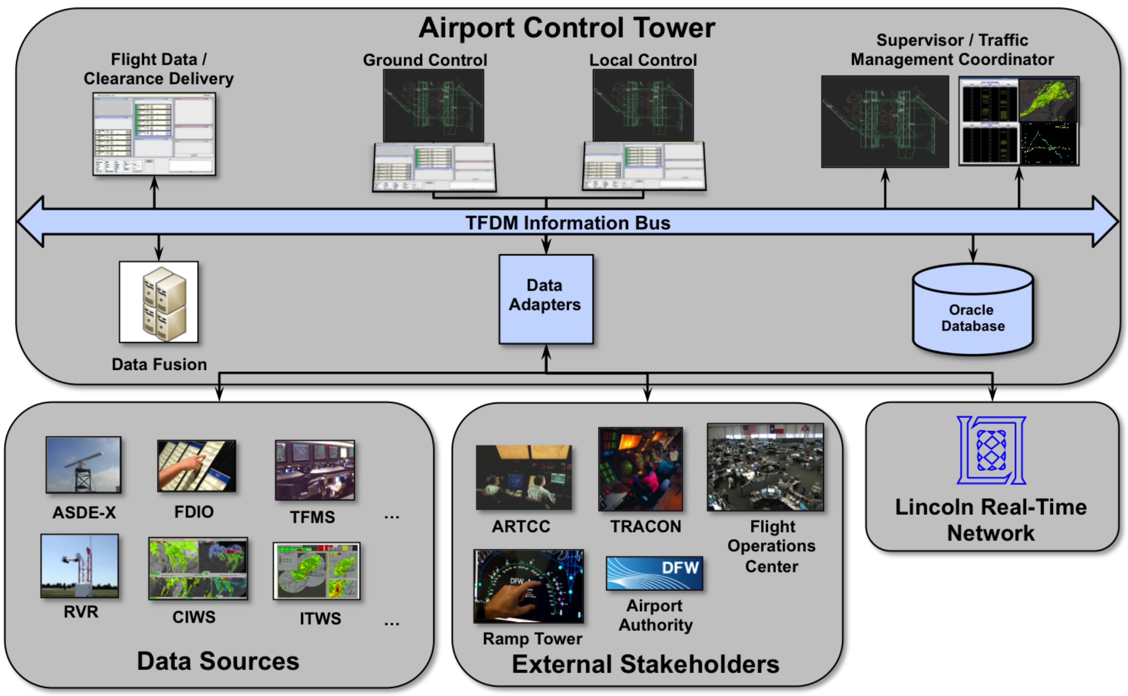


Figure 2: Tower Flight Data Manager System Architecture.

system employs a net-centric architecture to host its software components. This approach allows the system to be modular and extensible. Figure 2 shows the manner in which functional software modules such as adapters to other automation systems, computer-human interfaces (including an enhanced surveillance display known as the Tower Information Display System (TIDS), an electronic flight strip system known as the Flight Data Manager (FDM), and a traffic management display), and decision support tools (DSTs) interact with each other over a common TFDM information bus. The TFDM system architecture enables communications with existing and planned external automation systems that provide surveillance, flight, traffic management, and weather information. This system is also capable of providing surface situational awareness and decision support information (such as airport configuration, departure sequence predictions, expected departure times) to external automation systems. The ability for inter-system communications between facilities is expected to enhance collaborative decision making between users across different control facilities and yield a corresponding reduction in work load. The design of the TFDM prototype system and the component decision support functions has evolved with these interactions in mind.

A representative view of the information exchange between TFDM and other current and emerging National Airspace System (NAS) automation systems is provided in Figure 3. This view is continuing to mature through prototyping efforts similar to TFDM, which inform the types of interaction and information exchange that are needed in order to meet functional and performance requirements for an operational system. Figure 3 illustrates the broad range of systems that TFDM interacts with: consistency in the data, algorithms and assumptions used between these systems is of critical importance if the overall efficiency of the national airspace system is to be improved. The current interactions between TFDM and the other systems are described in turn.

TFDM is envisioned to interact with the Time Based Flow Management (TBFM) system to efficiently transition arrival and departure aircraft from the surface environment to the terminal and en-route environments. The TBFM system plans to employ time metering strategies for flow management. These strategies must be coupled with arrival and departure management strategies employed on the surface in order to achieve operational continuity and efficiency. Additional work is needed in the development and analysis of such strategies to inform the design of collaborative functions and interfaces between TBFM and TFDM.

The Traffic Flow Management System (TFMS) currently provides information about traffic management initiatives, estimated times of arrival, flight data, as well as trajectory information to TFDM. The TFDM decision support functions employ this information to develop early forecasts of flight arrival times and expected departure times. In the future, as the Route Availability Planning Tool (RAPT) capabilities are integrated into TFMS, constraints on flight routes due to weather will be available to TFDM in order to better plan departure operations. As emerging capabilities of the type envisioned by Collaborative Trajectory Options Program (CTOP) [12] also become integrated with TFMS, the air traffic control tower will be able to collaborate with en route and airline traffic managers to provide efficient tactical re-route strategies for blocked flights on the surface. There is also the potential to improve flight time estimates generated by TFMS using information provided by TFDM on surface traffic conditions. Although the TFDM and IDRP prototyping efforts have taken initial steps in integrating RAPT and certain limited traffic management information from TFMS, further work is needed to mature the concepts for collaborative re-routing.

The connection of TFDM with the En Route Automation Modernization (ERAM) system is the primary means by which tower automation will receive information about expected surface arrivals and departures. This connection also allows TFDM to provide updates to ERAM on precise arrival and departure times. This connection is also a key component for implementing new capabilities, such as tactical re-routes, where tower control can assist with filing alternate flight plans to enable more efficient departures. The bulk of the work in maturing and validating bi-directional

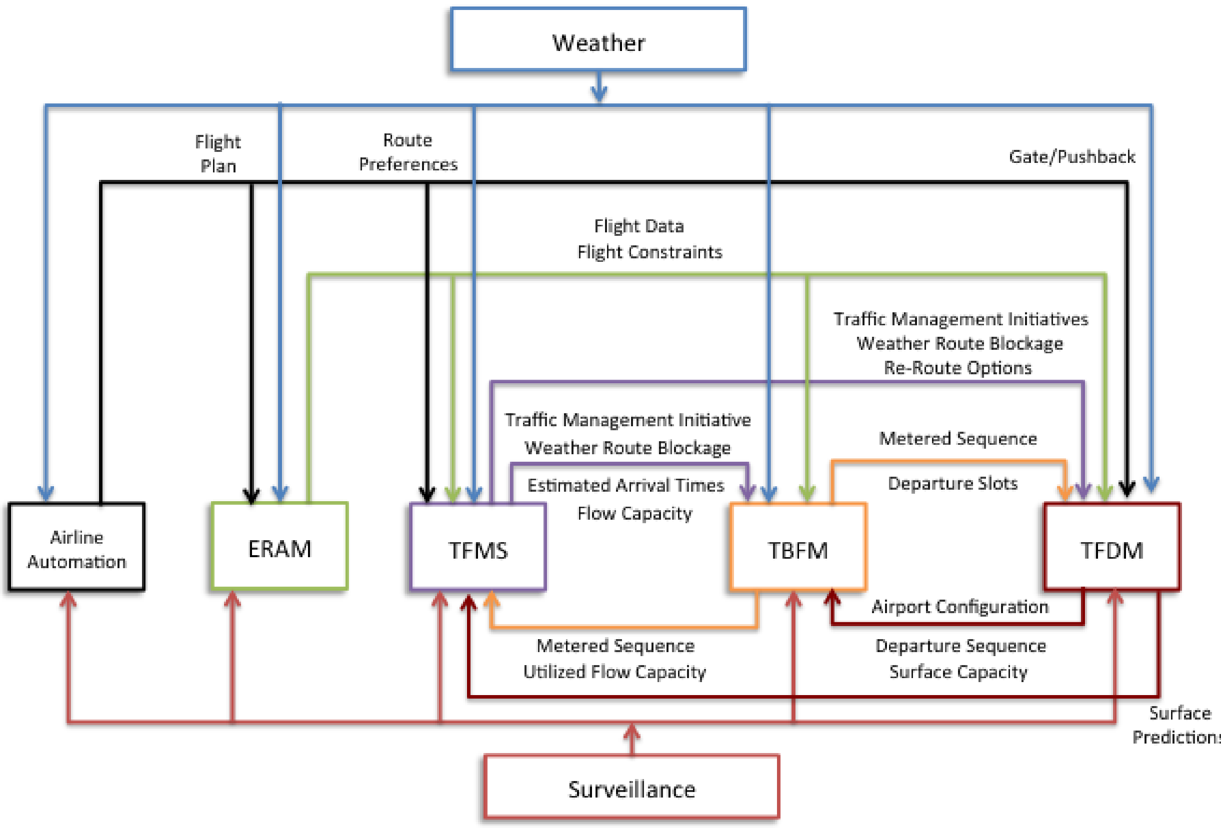


Figure 3: Inter-connection between TFDM and other NAS Automation Systems.

exchange of information between ERAM and TFDM still remains.

The communications interface with airline automation systems would provide information about expected push-back times for departures and gate assignments for arrivals and departures. This information is critical to providing accurate taxi time estimates, forming departure sequences, predicting gate arrival times, and estimating surface congestion. Focused efforts on maturing the interfaces with airline automation systems are still needed, for instance obtaining accurate and timely gate information.

In addition to flight and traffic management information derived from external systems, the decision support functions also require accurate terminal and surface surveillance, as well as weather data. This information is vital for decision support algorithms attempting to make accurate predictions about surface operations and suggesting alternative courses of action. Coordinated investments in the development and deployment of accurate terminal area wind/weather forecasts are critical to the operations of certain decision support functions, such as airport configuration.

There are additional NAS automation systems which the TFDM system is expected to interface with, such as: Runway Visual Range (RVR), Notice to Airman (NOTAM), and Digital Air Traffic Information Service (D-ATIS). Although these interfaces provide critical information to the tower controllers, their contribution to providing new benefits through consumer decision support functions is smaller relative to the benefit from other interfaces discussed earlier. Hence, we will not address these additional interfaces further in this report.

1.3 TFDM DECISION SUPPORT TOOL FOCUS AREAS

In this report we will focus on the following foundational and primary decision support functions: i) Runway Assignment, ii) Taxi and Arrival Time Prediction, iii) Terminal and Surface Wind Prediction, iv) Airport Configuration, v) Departure Metering, vi) Runway Sequencing, and vii) Departure Routing. These decision support functions enable the capabilities shown in Figure 1, and are therefore closely related to those capabilities. A notable exception is the *Taxi Routing* capability in Figure 1. This capability was not expicitly implemented in the TFDM prototype system due to it relative lower level of maturity. We have also considered *Terminal and Surface Wind Prediction* as a separate function. Although at present the primary consumer of *Terminal and Surface Wind Prediction* function is the *Airport Configuration* capability, it is expected that in the future this function will support other capabilities. The aforementioned decision support functions are highly coupled and expect to exchange information with other NAS automation systems. The interaction amongst decision support functions and other systems is captured in Figure 4. The solid colored boxes represent functions that are part of TFDM and the color lined boxes represent functions or systems external to TFDM. The horizontal lines represent information channels that facilitate information transfer from one function/system to a set of other functions/systems that might require the published information. The solid vertical lines represent information flow from TFDM internal functions, while the dashed vertical lines represent information flow from external systems. It would be cumbersome to trace all of the possible information flow threads in this coupled system. For illustrative purposes we have provided a simple thread of coupled interaction amongst the decision support functions using the numbered labels.

1. *Airport Configuration* establishes the runways to use based on wind direction, arrival and departure demand, surface congestion, noise considerations, metroplex impacts and controller guidance

2. Information about a flight arriving from ERAM, TFMS, or TBFM is processed and employed by *Runway Assignment* to recommend a runway for the flight (which can be superceded by controller input)

3. Based on the flight's intent, phase and other reference information, *Taxi and Arrival Time Prediction* estimates the time it would take it to reach the runway (assuming a departing flight)

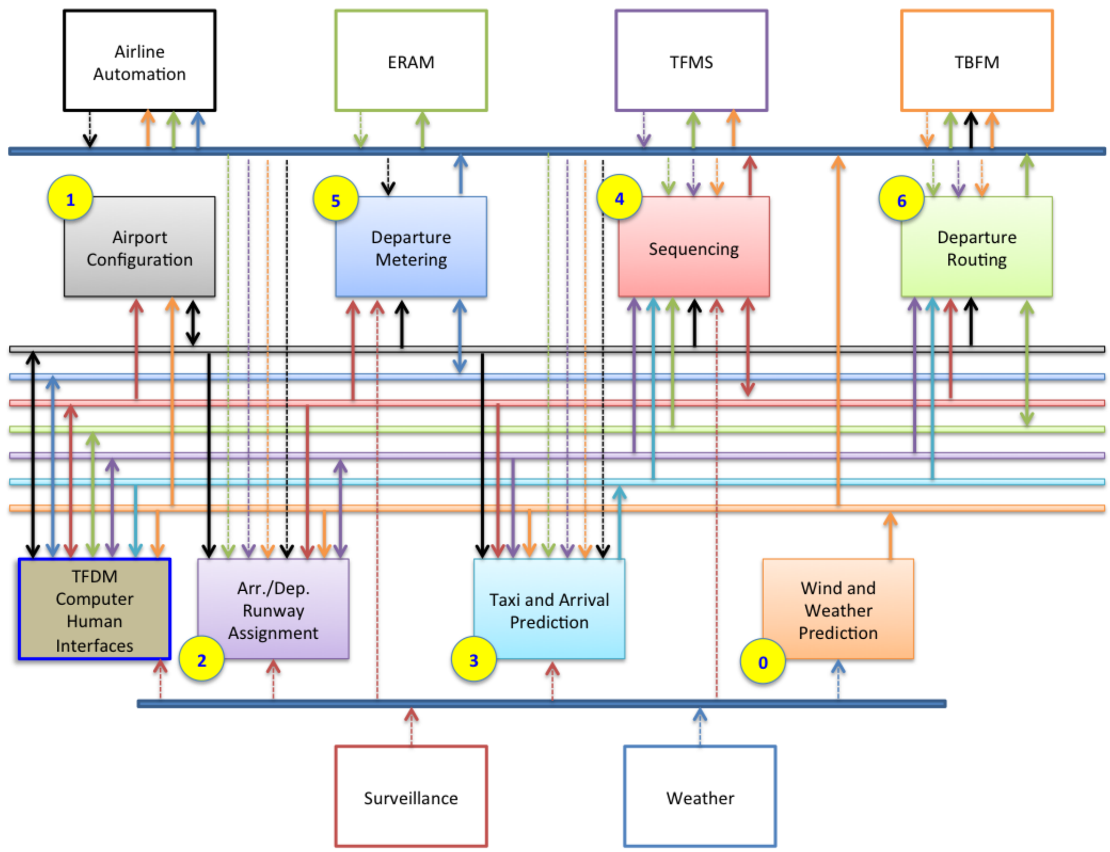


Figure 4: Coupling amongst decision support functions and other systems.

4. For the current configuration *Sequencing* employs taxi predictions, runway assignments, demand/congestion estimates, separation constraints, traffic management constraints and departure constraints to fit the flight into a recommended sequence (which can be further manipulated/constrained by the controller)

5. *Departure Metering* employs sequence predictions to generate a push-back recommendation for the flight (possibly in coordination with airline systems) in order to manage the overall surface demand as efficiently as possible.

6. *Departure Routing* integrates weather constraint data provided by *TFMS*, time-based departure constraints established by *TBFM*, route preferences from *Airline Automation* and surface sequence/congestion information internally from *TFDM* to coordinate a suitable flight route and departure time for the flight

This simple thread provides a basic sense of how decision support functions process flight and supporting data to generate recommendations to support efficient surface operations. The remaining sections of this report provide greater discussion on each of these decision support functions.

2. AIRPORT CONFIGURATION

2.1 OVERVIEW

Airport configuration defines the set of arrival and departure runways available for use during a given period. This definition can be expanded to include the availability of taxiways, and the coupling between runways and departure fixes. As such, the airport configuration defines the base set of available surface resources for flight operations, and therefore determines the maximum available capacity of an airport. These resources in turn govern the throughput or efficiency with which an airport can service air traffic demand. Selecting an appropriate airport configuration, as well as the time and duration for implementing that configuration, is often a challenge for air traffic control. The selection of an airport configuration is most often based on wind direction, noise abatement agreements, and traffic demand. The process of selection involves multi-facility coordination, because such decisions impact regional airports as well as the overall NAS traffic. Effective decision-making in multi-party environments requires uniform availability of accurate wind and demand forecasts at one or more airports. The re-orientation of arrival and departure operations during an airport configuration change can potentially incur delays at the airport. It is therefore not uncommon that air traffic control finds itself bearing the cost of implementing a correction in the midst of an unfavorable airport configuration. The rather significant challenges involved in cognitively and logistically implementing an airport configuration change invites a solution assisted by automation.

An automated tool for assisting airport configuration management must account for the effect of wind, weather and operational conditions such as noise abatement requirements and configurations at neighboring airports. Runway configurations are selected to comply with federal, local regulations and operator limits to the tail wind, cross wind and gust components specific to landing and departing aircraft. When these limits are exceeded, operations are moved to conforming runways. According to ASPM records [13], Boston Logan Airport experienced nearly 1900 configuration changes in 2010 (Figure 5), the majority of which were minor addition or removal of runways. In many cases, configuration changes result in a period of reduced capacity while ground and TRACON traffic are rerouted to align with the flows of the new configuration. During periods of high demand, configuration changes can result in significant surface congestion with excess delay, fuel burn, noise and emissions. Consequently, the selection, timing and frequency of configuration transitions are important considerations in reducing delays and emissions around airports.

The following subsections provide:

i) a selected survey of techniques available for affecting airport configuration change,

ii) results from simulations of an optimized sequence of configurations based on actual and predicted data suitable for the TFDM framework

iii) an assessment of benefits of such automation

iv) recommendations for incremental implementation of automated *Airport Configuration* selection in the TFDM framework

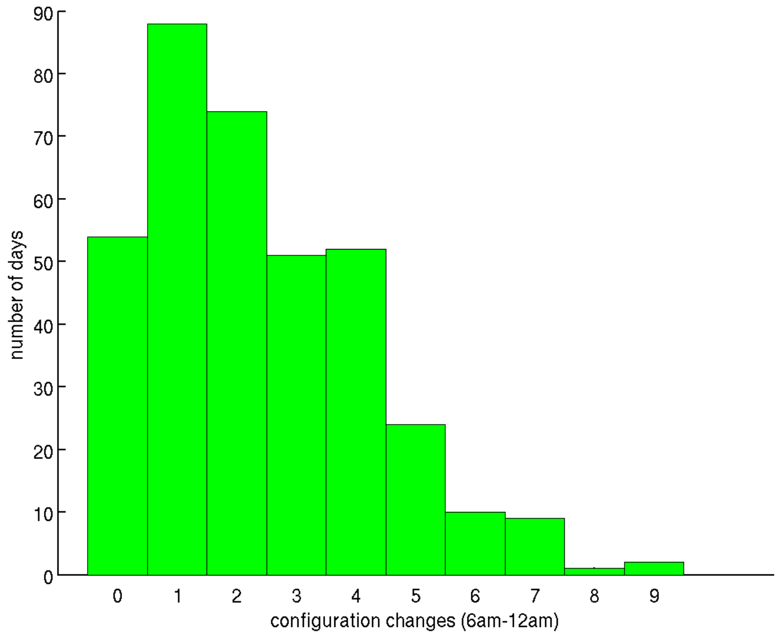


Figure 5: Histogram of airport configuration changes at Boston Logan Airport in 2010.

MIT Lincoln Laboratory's TFDM prototype implementation did not include a tool or algorithm that directly advises on an appropriate configuration change. There was also no facility for assessing the performance of one or more feasible configurations to allow controllers to coordinate judicious selections, other than a general view of demand available from arrival and departure timelines. It would therefore be of great value to implement and validate such a capability within a prototype system. Lincoln Laboratory has thus far evaluated a select set of airport configuration management techniques through the use of simulation.

2.2 STATE OF THE ART

At present no automated decision support tools are available to directly advise controllers on selection of airport configuration. This has led the FAA chartered Surface Technical Team Working Group (STTWG) [14] to recommended the following near term capability for inclusion into TFDM:

- [AC03] *Queuing/congestion analysis for permissible airport configurations in "What-if" planning* - Limited manual "What-if" planning tool to assess a single proposed configuration change at a specified time. Consider basic factors over next 60 min such as forecast traffic, winds, ceilings, and visibility. Could also consider departure route blockage and airspace configuration.

TFDM provides the infrastructure to gather information relevant to configuration change (current and predicted weather, current and anticipated traffic and local regulations) and therefore advise the configuration choice. However the underlying algorithms and techniques for judicious selection of airport configuration require further work.

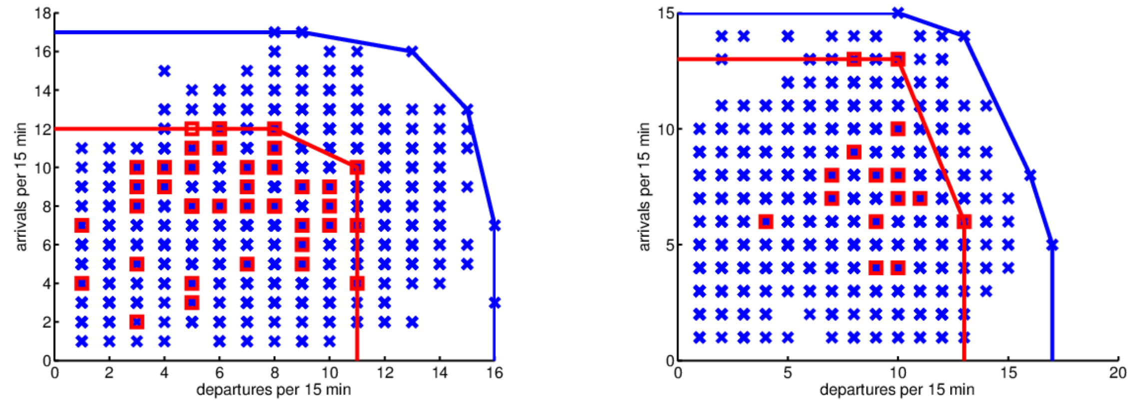
There is a recent body of work which seeks to emulate the process of runway configuration decisions and to improve efficiency beyond the current state. For instance, Balakrishnan [15] has proposed methods to model and emulate current configuration change patterns at airports. Gilbo [16] proposed a framework to optimize airport capacity based on demand. This model was later expanded to incorporate multiple configuration options and constraints at fixes around an airport [17]. Bertsimas and Frankovich [18] proposed an optimization model, itself an extension of the airport capacity optimization framework introduced by Gilbo, to decrease the unserved traffic based on demand and available runway predictions. Clarke et al. [19], and Duarte [20] have both proposed improved variants of the Bertsimas (Gilbo) model with sequential decision-making algorithms, dynamic programming and varying transitional capacities. Bertsimas [21] has more recently proposed a new model which favors runway selection over configuration. Such a model better couples with the other airport operation models.

2.2.1 Simulation Based Evaluation

The Bertsimas [18] approach was selected as representative of current state-of-the-art given that it integrates a number of methods in the existing literature and accommodates operationally-relevant constraints (e.g., provisions for uneven prioritization between arrival and departures, variable time costs for transitions and considerations for neighboring airports). This approach and many of its predecessors rely on Runway Configuration Capacity Envelopes (RCCEs), outer convex envelopes to arrival vs. departure counts during regular time intervals to represent arrival/departure tradeoffs. Each RCCE reflects the airport's ability to accommodate departure and arrival demand under various runway and wind directions, visual or instrument meteorological conditions (VMC or IMC), runway conditions and closures, noise abatement, surrounding airport configurations and other local conditions. RCCEs (illustrated in Figure 6) provide the basis from which to optimize runway configuration sequences (and hence airport capacity) over a given time horizon. In such a framework, un-served traffic is minimized within the set of feasible runway configurations.

2.2.2 Analysis Methodology

The approach outlined by Bertsimas [18] has been adapted and extended to support the needs of the future TFDM environment. The RCCEs are generated from historical airport arrival and departure operational data, as reported in the Aviation System Performance Metrics (ASPM) 2010 database, in 15 minute time intervals for each operating configuration. The set of all possible configurations generated from past year's RCCEs, reported in ASPM for 2010 (68 for Logan) is reduced to a representative macro group (5 for Logan), each representing its most prominent configuration. The optimized configuration is selected from feasible configurations at each time slot, in accordance to weather and other input conditions. Alternatively, the selection of feasible configurations can be created from parsing historic data to identify attributable relationships between historic runway configuration, weather and other operational data. Input from air traffic control personnel at



(a) 22L, 27 | 22R

(b) 27, 32 | 33L

Figure 6: Sample BOS RCCEs in 2010. The data is taken from the ASPM database. VFR and IFR data points are respectively depicted in blue and red.

airports of interests provided additional operational validity to the models. The all-inclusive set of feasible configurations then drives the optimization engine to determine what portion of arrival and departure demand can be serviced by each configuration in the feasible set.

2.2.3 Data Sources

Archived meteorological data (METAR) from OGINET (both hourly and special advisories) as well as the FAA Aviation Performance Metrics (APM) database provided the critical data necessary for the study. APM provided past statistics on actual arrival and departure demand as well as runway configuration usage per quarter hour. The FAA ASPM database yielded individual flight information for each airport during the years of interest. This data helped correlate artificially generated bin counts (15-minute) to individual flight delays.

In addition to the published databases, this study included data from observations and interviews obtained during field visits to New York and Boston centers, TRACONs and towers. The visits to various towers in the Northeast provided important insight from the controller's perspective as well as operational observations.

2.2.4 Runway Configuration Capacity Envelope

The methodology used in this study depends on the availability of runway capacity envelopes for the airports of interest, and the faithful capture of airport capacity performance statistics through these envelopes. These envelopes were estimated from historic data, with particular attention to years during which the airport operated at high capacity. Such (maximum capacity) years provide a sense for the operational limits of the airports. In the case of Boston, FAA ASPM data counts were used to generated the RCCE curves for VMC and IMC weather conditions. The higher traffic volume in 2001 (424,445) as opposed to 2010 (346,844) is reflected in the RCCE curves, as shown in Figure 7. Observations indicate that the RCCEs generated do characterize underlying configurations reasonably well.

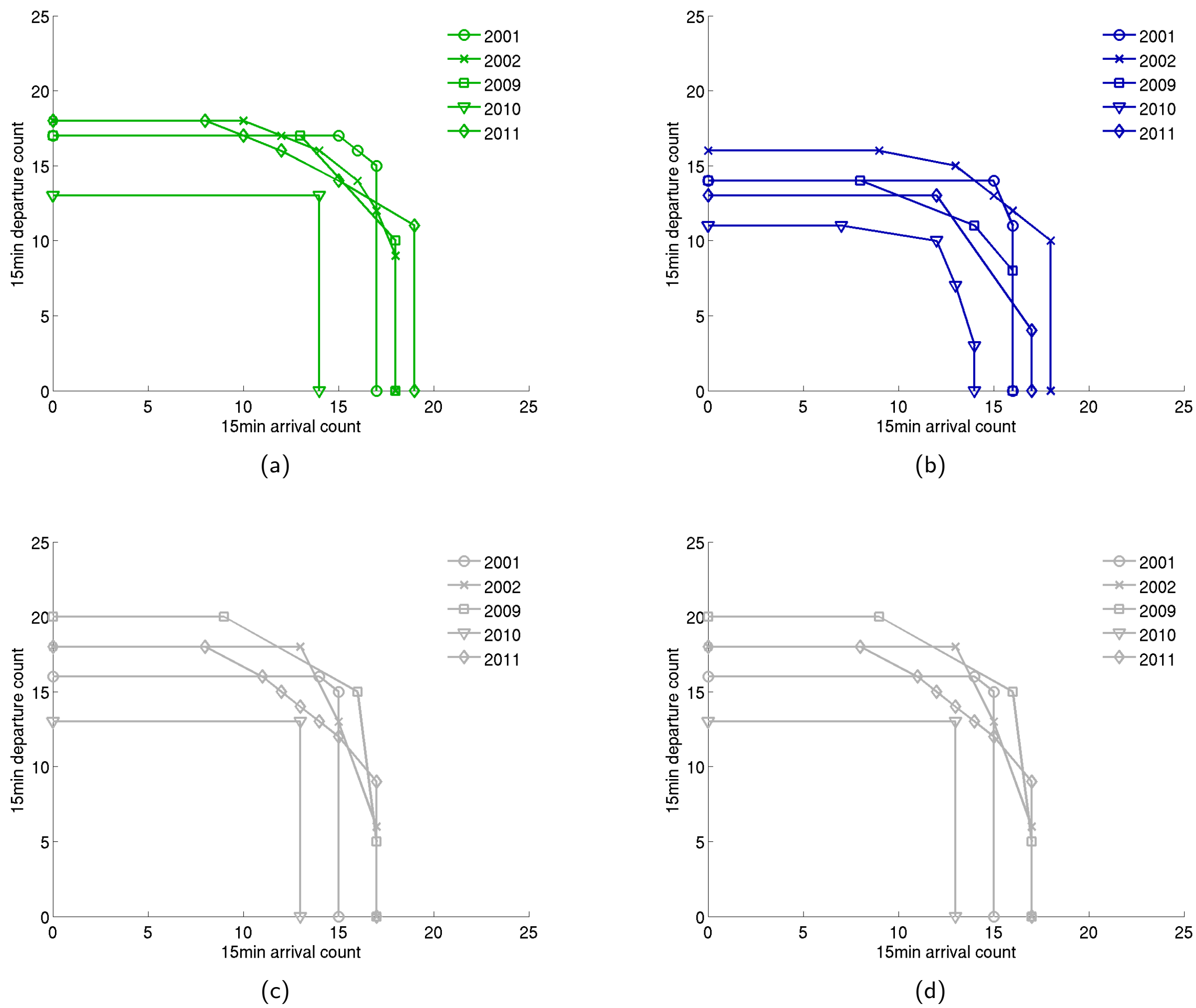


Figure 7: Runway capacity envelopes for Boston Logan's top configurations in 2001, 2002, 2009, 2010 and 2011.

Reported configurations can be clustered into groups comprised of collaborative runways. An important consideration regarding capacity envelopes is the balance between sufficiently discriminating configurations and maintaining an excessive number of configurations. For instance, FAA ASPM data for Boston shows their use of 67 different configurations during the year 2010. Many of these configurations are related but the exact demarcation between configuration is not always clear. During the course of this study, we initially clustered the configurations into the highest used supersets. The result was a reduction from the 67 configurations to 20. It was later decided to fold all configuration into 5 basic subgroups, after consultation with the BOS Tower personnel.

2.2.5 Feasible Configurations

The optimization engine employed for this study was aimed at finding the best configuration under a set of operating constraints over a time interval. At each time interval, the engine is presented with a set of all-inclusive feasible configurations, each consistent with current meteorological and demand conditions. An optimal trade-off between capacity allocation and runway configuration choice is then selected. The all-inclusiveness of the feasible set is critical as is the exclusion of all non-feasible configurations from the set. An evaluation of the many factors influencing the feasible set selection at at Logan airport (wind direction and seasonal correlations shown in Figures 8 and 9) concluded that the overriding contributing factors are weather and demand. This observation was confirmed by controllers at Logan, JFK, LaGuardia, and Newark. Demand trade-off is also reflected in the capacity envelope curves. Other predictable factors include noise abatement schedules, runway repair and maintenance.

The inclusion of a configuration into a feasible set is based on a maximum tailwind of 8 kts and a maximum crosswind of 25 kts. This rule was shown to be 99% inclusive at Boston and DFW over the recorded configurations data for 2010.

2.2.6 Airport Scope

This study primarily focuses on Boston, but includes some analysis of Dallas/Fort Worth (DFW) Airport. The relative isolation of these airports from neighboring airports simplifies the study. Dallas Fort Worth Airport differs from Boston in its higher demand and lower variability in runway directions. DFW's fewer unique runway directions translate into fewer unique configuration options. The choice of study airport reflects the research team's extensive knowledge of BOS operations, including configuration groupings. The techniques developed here can be employed in analyzing configuration performance for a larger set of airports. Such an analysis is expected to be valuable to support the FAA's Final Investment Decision (FID) benefits assessment processes.

2.2.7 Results and Observation

Two performance ranges are reported in this study. The lower performance range reflects an imposition of a 15 minute down time (penalty to both arrivals and departures) on every configuration change; the upper performance range represents no penalty for configuration changes. The 15 minute down time is a fairly harsh penalty considering that most configuration changes are coordinated well in advance; therefore this scenario is considered to generate a conservative lower performance bound. The optimizer was set up to provide preference to arrivals over departures.

Results for future years are computed assuming meteorological conditions similar to 2010 and using the most accommodating capacity curves observed in past years. Future benefits through optimization are shown in Figure 10.

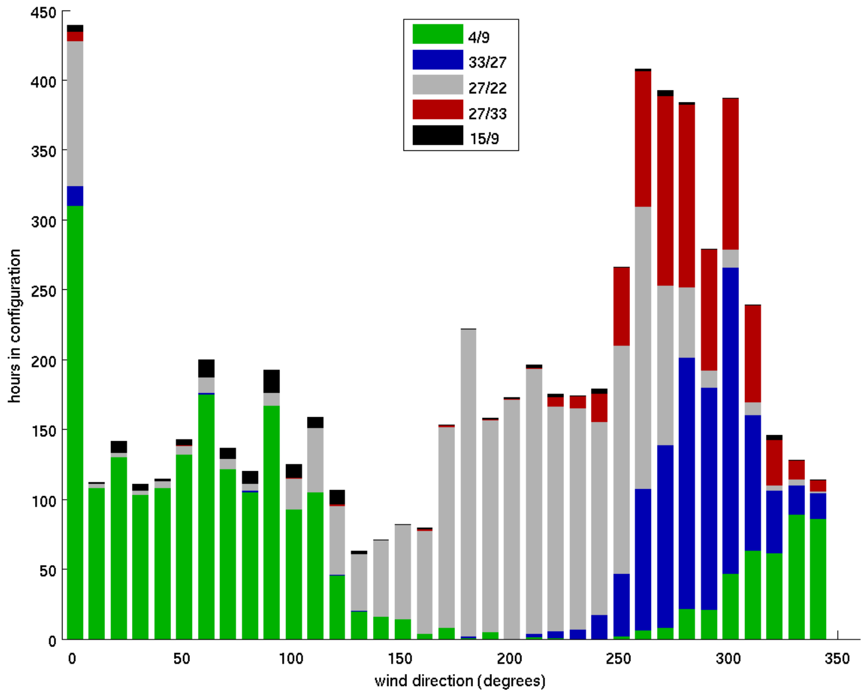


Figure 8: Total hours in configuration per wind direction at Boston Logan in 2010. The cluster of gray (27/22) in the middle is an example of high usage of configuration over a range of wind directions.

The BOS aggregate delay savings from 2015 to 2035 are estimated to be over 13,000 hours for arrival flights and approximately 60,000 hours for departures, while for DFW the aggregate numbers are 10,000 hours for arrivals and 90,000 hours for departures. These translate to fuel savings of 16 million gallons ($39 million) for BOS and 26 million gallons ($62 million) at DFW. The savings are accentuated with the cost attributed to a configuration change. The greater the configuration change delay costs, the greater the potential benefits. The specific configuration change delays vary with traffic, runway configuration and airspace. The potential benefits to optimizing configuration change in Boston would have led to 4-8 hour delay savings per day. The following observations are made regarding Figure 10: 1) Departure delay savings are naturally higher than arrival delays due to the greater priority given to arrivals. This difference is reflected in the results presented. 2) The range of benefits in Boston is greater than that for DFW due to the higher number of configuration choices in BOS. 3) The benefits at BOS are nearly constant over the years, while DFW sees an increase in benefits. This difference is likely due to BOS operating closer to maximum capacity, compared to DFW.

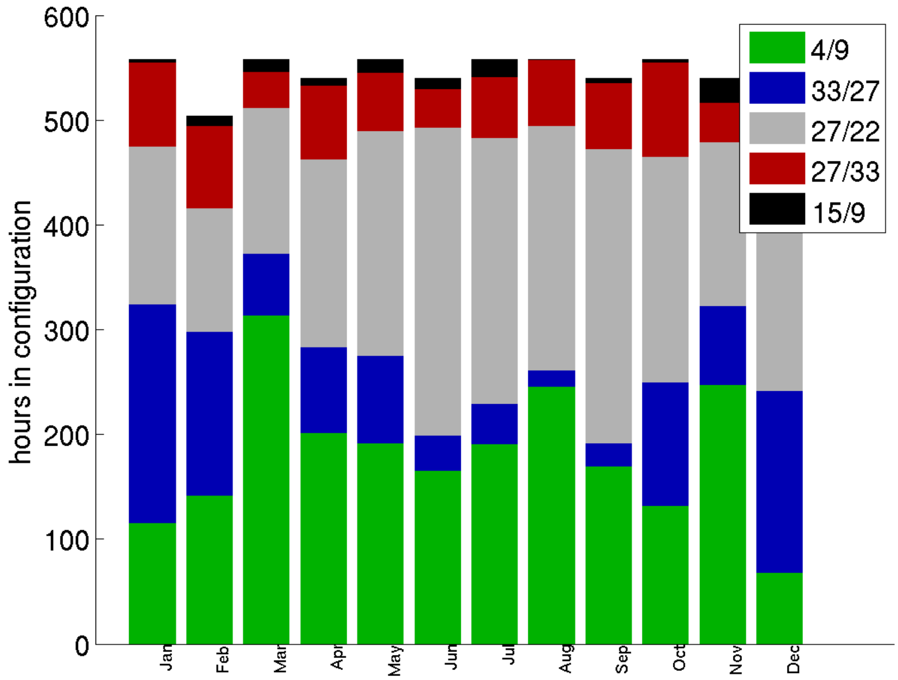


Figure 9: Seasonal configuration usages at Boston Logan in 2010. Usage of configuration 27/22 (gray) and 33/27 (blue) are increased during summer and winter months, respectively.

2.3 TFDM PROTOTYPE CAPABILITY

The implementation of airport configuration in the TFDM prototype was limited to a selection of pre-defined configurations. Feedback from controllers involved in the evaluation of the TFDM prototype at the DFW airport trial noted: i) a unified configuration management function within the tower to be useful and ii) an automated tool to advise on configuration change would be beneficial.

2.4 OPPORTUNITIES FOR IMPROVEMENT

The current state-of-art for airport configuration still lacks automation within the decision support tool. The development of such tools will involve the maturation of wind forecasts, which are a prominent consideration in the selection of a good configuration. Further refinement and effective evaluation of candidate airport configuration optimization algorithms also depends on the development of a wind forecast capability. Since airport configuration management is a collaborative decision making process, the development of collaboration tools and their human-factors evaluation are also important in delivering an operationally useful capability.

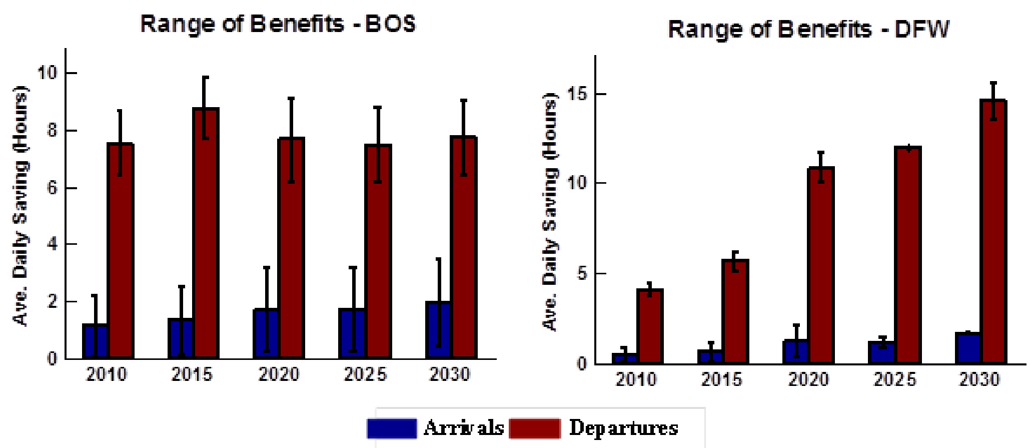


Figure 10: Estimate range of benefits of optimizing configuration usage at BOS and DFW.

Recent proposed algorithms for airport configuration selection do away with configuration change in favor of direct selection of runway, and couple this selection to other airport surface operations. Such an approach is more precise and requires higher data integration, but is perhaps less robust. The following recommendations provide a roadmap for incremental implementation of airport configuration implementation, each step with direct benefit to controllers:

1. Feasible configuration sets: given the current weather conditions and operational constraints, provide the controller with the set of all feasible configurations
2. RCCEs for each configuration: provide an RCCE for each configuration with overlay of current and future demand
3. Advise on most accommodating configurations based on the feasible set (modifiable by controllers)
4. Provide predictive recommendations for when to change configurations to meet demand and minimize delays
5. Couple configuration change guidance across airports in a metroplex

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3. RUNWAY ASSIGNMENT

3.1 OVERVIEW

The assignment of runways is a routine function that must be performed by air traffic control for each arrival and departure operation. The assignment of arrival runway is typically the responsibility of the TRACON, while a flight's departure runway is assigned by the air traffic control tower. Present day operations (and possibly near-term future operations) do not require that this function be performed with the aid of automation. The need for automation only arises during congested or high demand periods when runway assignment for load balancing to achieve greater efficiency induces a high cognitive load. However, the foundational nature of this function is the primary factor that drives the need for an automated capability. Most of the other key decision support functions, such as *Taxi and Arrival Prediction*, *Sequencing*, *Departure Metering*, and *Departure Routing* require knowledge of a flight's runway for producing accurate forecasts about surface operations.

An automated runway assignment capability requires information such as – flight data, flight intent, airport configuration, origin gate, current position, and local operating procedures – in order to determine the appropriate runway before and after push-back. In this section we discuss the assignment of runway for arriving and departing flights, and the role of automation in assisting with the assignment. The current runway assignment function in the TFDM prototype system implements a rule based approach to selecting a suitable runway for a flight. This function relies on constraints provided by other modules, such as the airport configuration, which sets the direction of runway usage, the type of operations for each individual runway, and the availability of the runways. The rule base approach can be extended to accommodate load or congestion constraints to improve efficiency of runway use. This approach is expected under most circumstances to make operationally appropriate runway assignments. The runway assignment approach followed by the TFDM prototype (which is based on Surface Decision Support System (SDSS) and Surface Management System (SMS)) is not in general expected to yield optimal runway assignments. In order to provide optimal runway assignments, the solution approach would require a significantly more complex consideration of the coupling between runway utilization, demand and the separation requirements between individual aircraft. The following subsection briefly reviews investigations into approaches for making optimal runway assignments. The recommended near-term capabilities for runway assignment are also stated. These near term needs have served as our rationale in adopting the SDSS rule based approach for runway assignment in the TFDM prototype. We subsequently comment on the additional efforts needed to mature the runway assignment capability.

3.2 STATE OF THE ART

Runway assignment is a foundational capability within the TFDM prototype system. In general runway assignment may be considered a component of an overall surface management optimization strategy. For example, a runway assignment study by Kim et al. [22] accounts for separation rules between aircraft, transition costs from fixes to runways and taxi costs from runways to gates which are often covered by Sequence Optimization and Taxi Routing modules in integrated approaches [21, 23]. Integrated or unified approaches have been tested only in simulation. The study by Bertsimas and Frankovich [21] provides a unified optimization framework for surface operations whereas the study by Griffin et al. [23] describes the result of combining individual optimization modules which could potentially yield sub-optimal solutions since the integration has not been formalized.

The design and implementation of the runway assignment capability for TFDM has followed the recommendations of the FAA chartered Surface Technical Team Working Group. The primary recommended capabilities adopted by the TFDM prototype are:

- [RN01] *Assign departure runway based on pre-defined rules and display to controllers* - This capability provides runway assignments displayed to the controller on an electronic flight strip. The runway assignment is made based on pre-assigned rules which may consider factors including airline, gate, departure fix, destination, aircraft type, airport congestion, and taxi time. The default runway assignment can be changed by controller. Automation is expected to update the runway assignment when the flight is re-routed or the departure fix changes.
- [RN08] *Provide real-time runway assignment rule creation by controller* - This capability allows controllers to use new rules for runway assignment related to airport configuration. The new rules may be the result of runway or taxiway closure, temporary flight restriction, or nearby convective weather.

3.3 TFDM PROTOTYPE CAPABILITY

The runway assignment capability delivered in the TFDM prototype included the ability to view a suggested runway assignment in a runway assignment field, within the Flight Data Element (FDE), which maintains current flight data, for departures. There is also the capability for the controllers to easily change this runway assignment, and the ability to view arrival and departure demand by runways. Assignment of runways is performed using a rule-based approach that selects the runway whose attributes best match elements within the flight data (such as a matching the departure fix to runway-to-fix mapping). This decision support tool updates the runway assignment field for a flight whenever Flight Data Input/Output (FDIO) system sends an updated route to TFDM. It also provided a capability for users to change the runway-to-departure-fix mapping on the Supervisor Display in accordance with DFW procedures; TFDM then subsequently propagates this change to the individual FDEs at Ground Control (GC) and Local Control (LC).

Technical performance of the runway assignment module was assessed by how well the algorithm logic mapped to the actual runway assignments used. Over the course of the six days of testing at DFW airport, involving several thousand flights and numerous (simulated and actual) instances of closed runways and runway-to-fix mapping changes. Over this time 98% of the final runway assignments at the queue for departures were consistent with the default logic implemented in the TFDM prototype.

Runway assignments for individual flights are based on the flights' filed departure or arrival fix.

The runway assignment algorithm suggests new runway assignments when the airport configuration changes, the departure procedure changes, a runway is closed or opened, or a runway to fix mapping changes. The algorithm is based on a set of default mappings between fixes and runways that are segmented according to their location on either the East side or the West side of DFW. The schematic in Figure 11 presents the DFW fixes and their default assignment to runways for jet departures in each airport configuration. The default runway assignment for propeller aircraft is 18R in a Southflow configuration and 31L in a Northflow configuration. The runway assignment rules are different for departures and arrivals and are described separately.

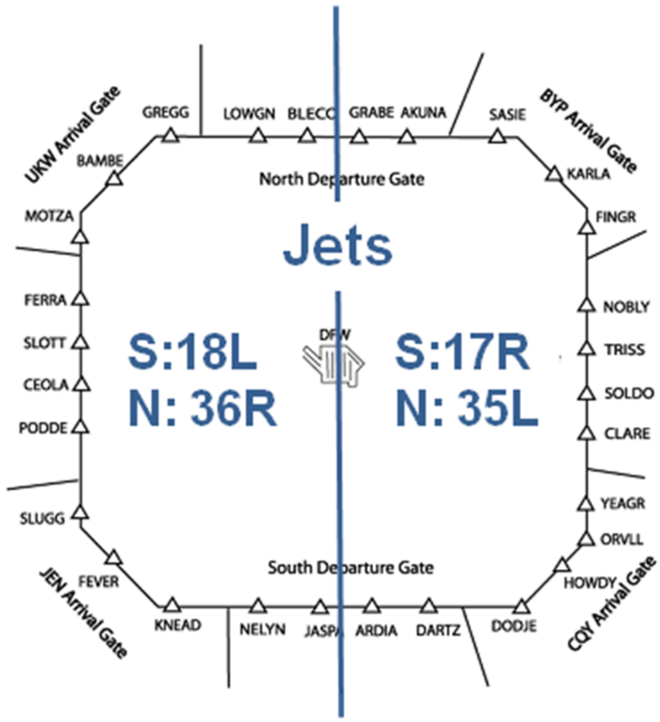

Figure 11: Jet departure runway assignments based on departure fix and airport configuration.

A departure flight's runway assignment is based on the flight's filed departure fix and the current runway-to-fix mapping. The supervisor can over-ride the default logic by modifying the runway-to-fix mapping through the Supervisor display. The departure runway may change automatically as updates are made to the flight's flight plan route within the FDIO system. When a flight's departure fix closes, no specific action is taken by the DST; a flight plan update from FDIO triggers the runway assignment to be recalculated. Such changes may occur only until the flight's taxi clearance is issued. A controller may change a flight's runway assignment manually, after which time the DST will no longer automatically update the flight's runway assignment. Whenever one of these primary departure runways is unavailable, the logic assigns secondary and tertiary runways as alternates according to a static logic set presented in Table 1.

Note that it is quite common for aircraft to depart "off hat" at DFW, i.e., on runways different from the default mappings (and different from other aircraft filing a given departure procedure) in order to balance demand across the airport or to reduce taxi distances for certain flights. For example, BLECO3 departures typically depart from 18L/36R. If that runway had a lot more demand in a given time period than 17R/35L and a BLECO flight left terminal A on the east side of the airport, the east side ground controller could coordinate with the west tower to keep a "one off" BLECO3 aircraft for departure on 17R/35L. These types of tactical decisions are not currently captured by the automatic runway assignment DST and must be manually entered by the controller.

An arrival flight's runway is assigned initially by using its flight plan's arrival fix and a static arrival runway-to-fix mapping that assigns East side fixes to East side runways and West side fixes to West side runways. When an arrival is approximately 20 NM from DFW, the algorithm switches to using track data from ASDI/TFMS. The arrival runway is assigned based on a straight line trajectory of the aircraft position and does not currently incorporate speed, heading and altitude. The algorithm uses backup runway assignments in the event of a runway closure as enumerated in Table 1. Note this is a highly simplified rule-set: the operational consequence of a closed runway often leads to traffic flows being re-directed to numerous different alternate runways to better balance demand across the airports depending on the specific characteristics of the demand at the time.

TABLE 1: Default and Backup Runway Assignment For Different DFW Airport Configurations

Southflow Configuration	**Northflow Configuration**
17R → 17C → 17L	35L → 35C → 35R → 36R
17C → 17R → 17L → 18R	35C → 35L → 35R → 36L
18L → 18R → 17R	36R → 36L → 35L
18R → 13L → 17C	36L → 36R → 35C

3.4 OPPORTUNITIES FOR IMPROVEMENT

Improvements to the runway assignment logic would potentially include leveraging the performance of the wheels-on time estimation algorithm for arrivals described in Section 4. The algorithm (based on ensemble tree learners) would be trained on historical ASDI/TFMS track data along with Flight Plan information. The wheels-on time estimation algorithm has been shown to function just outside the TRACON boundary (80 NM – 60 NM from airport), so the expectation is that the Runway Assignment algorithm would also function at that distance. Preliminary results of estimating arrival runway assignment based on similar features showed performance similar to that of the wheels-on time estimation.

Further work on runway assigment should also consider the variablity of applicable runway assignment rule-sets for different airports. Therefore there is a need for an adaptation approach which will allow the creation of rule-sets to be generalized for a broad set of airports.

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4. TAXI AND ARRIVAL TIME PREDICTION

4.1 OVERVIEW

However, Predicting the amount of time a flight is expected to take during taxi or descent, as well as its impact on the operation of other flights is cognitively challenging. The ability to make such predictions accurately several minutes in advance of a flight arrival or departure is a key factor in developing efficient recommendations for human controllers. This task is challenging due to the inherent variation in taxi and descent times due to their dependency on a range of inputs from internal functions and external systems such as – the layout of the airport, local operating procedures, aircraft type, airline carrier, gate location, assigned runway, surface congestion – to name a few. The human controller does not typically have high interest in the taxi time or descent time as a separate quantity. However the development of accurate and robust algorithms for taxi and descent time prediction is a foundational need for other decision support functions involved in surface traffic management. The goal of a taxi time prediction algorithm is to estimate the time it takes a given departure or arrival aircraft to reach a particular feature of interest on the airport surface. For departures the predictions are typically made for spot egress, queue entry, runway threshold crossing and wheels-off times; for arrivals they consist of wheels-on and gate-in times. Taxi time predictions are envisioned to play a critical role in, among other things, the optimization of push-back times and runway departure sequences with respect to delay and throughput, the timing of airport configuration changes, and the efficient and timely delivery of departing aircraft to the runway in order to take advantage of route openings in the overhead stream. The latter is especially pertinent during inclement weather and/or during heavy traffic volume, where the time window during which an aircraft must take off and merge into the overhead stream can be very narrow. In addition, taxi time predictions displayed on runway sequence timelines can provide valuable situational awareness to air traffic controllers. In the following subsection we discuss approaches for taxi time and arrival prediction employed in this and other efforts. We then discuss the taxi and arrival prediction approach implemented in the TFDM prototype tested at DFW, and its performance. We note at the outset that the capability evaluated at DFW employs a simple approach, employing off-the shelf algorithms, to make taxi and arrival time predictions. As such, this approach is unable to provide accuracies sufficient for operational use. The last subsection discusses further work needed to mature, integrate, and validate algorithms that provide operationally adequate accuracy.

4.2 STATE OF THE ART

In the following we discuss techniques employed by a set of deployed systems and field-tested prototypes in computing taxi times.

Traffic Management Advisor

wheels-on time predictions for arrivals are currently available in the field through the Traffic Management Advisor (TMA) tool [24]. However, this tool, to date, has limited deployment and relies on knowledge of routing decisions made by controllers to make accurate predictions. TMA Estimated Time of Arrival (ETA) predictions are based on detailed deterministic physics-based models that incorporate airport configuration, winds aloft, aircraft types and separation and/or flow rate constraints. However, TMA does not explicitly account for uncertainties inherent in real operations, such as deviations from standard arrival routes. In addition, aircraft seldom fly at exactly the modeled (deterministic) speeds or along the assumed trajectories. Other methods have been proposed to deal with the uncertainties inherently present in aircraft trajectories. In [25], the authors propose a hybrid linear approach which uses Interactive Multiple Model (IMM) and particle filtering with resampling. In [26], the authors use regression methods based on tree-based ensemble methods to predict ETAs and provide uncertainty bounds. Other deterministic physics-based models have been tested in the literature as well [27]. Unfortunately, it is difficult to compare the predictive accuracies of these algorithms because they are tested on different days and at different airports.

Surface Management System

Event time predictions for runway departures is one of the capabilities of SMS [28]. Since its development in the late 1990s SMS has been field tested in various locations: Federal Express and Northwest Airlines Ramp Towers at the Memphis International Airport as well as at the United Parcel Service facilities at Louisville International Airport. SMS is also installed at the center tower of the DFW airport to support NASA research and is part of NASA Ames' *FutureFlight Central* testbed facility. The prediction accuracy of wheels-off times tested at Dallas/Fort Worth (DFW) airport, using SMS algorithms was analyzed by Monroe [29]. The prediction accuracy is determined by an error of no more than 1 minute from the actual runway departure time. The results of that analysis found taxi time estimates gaining in accuracy as surveillance data became available and predictions were updated. Since the typical taxi time at DFW is about 10 minutes, the accuracy improves starting 10 minutes before the actual wheels-off time. For time horizon greater than 10 minutes, less than 10% of flights had the correct predicted wheels-off time. SMS predicts wheels-off times for flights using planned push-back data from Enhanced Traffic Management System/Aircraft Situation Display to Industry (ETMS/ASDI) data or actual push-back event data along with complete real-time surface surveillance data and model of aircraft's performance as the aircraft begins movement.

Taxi time predictions are also a part of the CDQM [6] and SDSS [30] tools from Mosaic ATM. The hybrid network event model used by these is closely related to the one implemented by SMS.

Other algorithms

Availability of real-time Airport Surveillance Detection Equipment, Model X (ASDE-X) surface surveillance data has enabled improvement of taxi time algorithms by various researchers. Regression-based techniques with a variety of predictive variables have been used by [31–33]. The models are difficult to compare since they are tested on data from different airports. Note that the models developed by MITRE [32] and MIT Lincoln Laboratory [33] are somewhat similar in their approaches. The proposed methodologies construct separate predictive models for various segments of the taxi route: ramp, taxi, and queue, and use a variety of prediction variables, such as departure/arrival rates and weather. The difference lies in the regression techniques used by the researchers: the former uses linear regression while the latter uses statistical learning techniques. The linear regression models in [32] showed improvement over the currently available taxi predictions from ETMS or using average taxi-out times at John F. Kennedy Airport: they reduced mean prediction error (predicted actual taxi-out time) from −8.07 (ETMS) and 2.29 (Averages) to 0.68 minutes, while the error spread (standard deviation) was reduced from 21.78 (ETMS) and 8.13 (Averages) to 4.61 minutes. The statistical learning models in [33], illustrated here in Figure 12, exhibited improvement over the ordinary least squares (OLS) or linear regression techniques at Dallas/Fort Worth Airport: they reduced the mean absolute error from 0.54 (OLS) to 0.44 minutes while the maximum absolute error was reduced from 2.7 to 2.1 minutes. While the two methods cannot be compared directly, the evidence shows that statistical learning methods can improve accuracy of the taxi predictions. In addition, some statistical learning methods, like Quantile Regression Forests, can be use to quantify uncertainty associated with each individual point prediction [26].

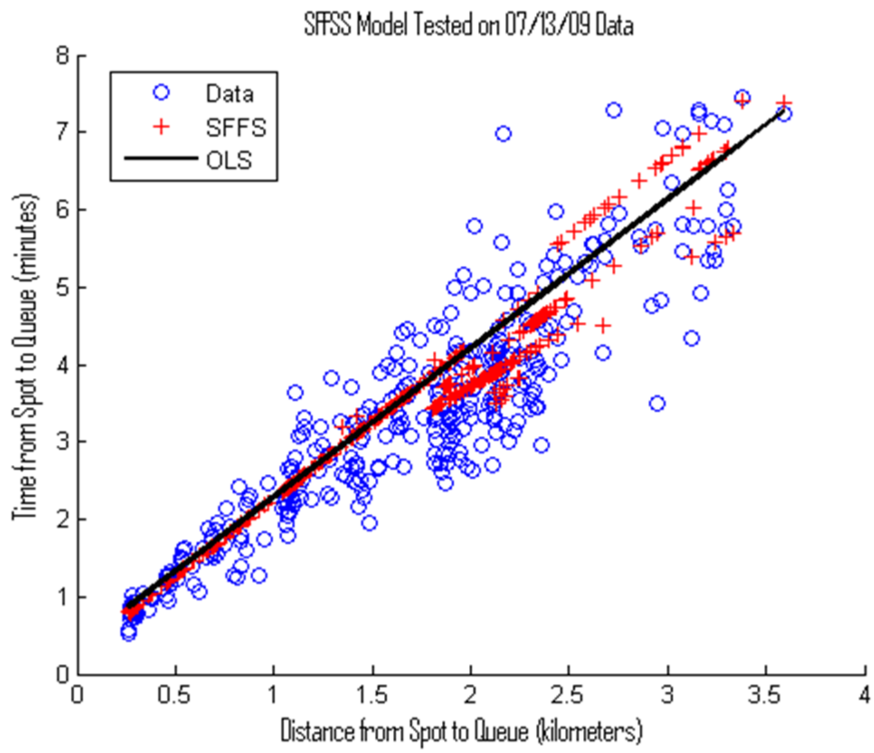


Figure 12: Comparison of Linear Regression (OLS) and Statistical Learning (SFFS) methods for taxi-out Predictions at DFW [33].

However, these models have not yet been implemented to support robust, real-time operation. One of the uses of taxi time predictions is for forecasting the length of the queue fifteen or more minutes in the future for use in departure metering as described in Section 6. At some airports, like DFW, this would imply that taxi times and queue occupancy times need to be estimated when most of the departures have not yet pushed-back from the gate. In other words, most of the explanatory variables such as departure and arrival rates have to be forecasted, which introduces uncertainty into taxi predictions. In addition, uncertainty associated with the actual push-back times and its effect on the resulting accuracy of taxi time estimates has not yet been comprehensively assessed. While reinforcement learning techniques described by [34] may be able to better adapt to the stochastic nature of runway operations when compared to parametric regression models, their accuracy was not directly compared to statistical learning techniques such as Quantile Regression Forests [26].

4.3 TFDM PROTOTYPE CAPABILITY

A basic taxi and arrival time prediction capability was included in the TFDM prototype system evaluated at DFW airport. Wheels-off predictions for departures and wheels-on predictions for arrivals were used to display predicted departure sequences and expected arrival and departure demand on the supervisor display. In addition, the predictions were used by Departure Routing and Surface Metering DSTs. In particular, expected arrival and departure sequences were adjusted to accommodate miles-in-trail/minutes-in-trail/arrival rate constraints on individual flights that were manually entered by the controllers. Taxi time predictions were also used to estimate queue length so that the Surface Metering algorithm could recommend spot release rates to the Ground Controller with a goal of keeping the length of the departure queue at an optimal level.

The accuracy of the taxi time algorithms tested at DFW is summarized in Figures 13 and 14. The bars represent the percent of flights with errors less than 2 minutes. As is annotated in the figures, the flight coverage is significantly less for flights 15 and 30 minutes from their actual wheels-off/wheels-on time. This is because the SDSS derived taxi prediction algorithms in the TFDM prototype suffer in their error performance with increasing time horizon. Since many operational decisions about sequencing aircraft and any future recommendations of airport configurations would require accurate estimates 15–30 minutes from takeoff, the algorithm's accuracy and coverage need to be improved.

To support future development of decision support tools, research has been conducted to identify techniques for improving taxi time estimates. In particular, the predictive accuracy of taxi out models using linear regression and statistical learning methods have been compared for Dallas/Fort Worth Airport [33] and statistical learning methods have been applied for predicting ETAs for arrivals in [26]. As is pointed out in [26], the advantage of using tree-based ensemble methods, such as Quantile Regression Forests (QRF), for generating predictions lies in the fact that in addition to providing accurate point predictions, the algorithms generate conditional probability distributions for each individual flight. These can then be used to estimate conditional means, higher order moments, conditional quantiles and prediction intervals, which can be used to attach a measure of confidence to individual predictions.

The variability of prediction intervals for predicting ETA at Dallas/Fort Worth International Airport is illustrated in the figures below. Figures 15a and 15b show that the 90% prediction interval widths decrease as these arrivals approach the landing runway. Note that the 90% prediction interval

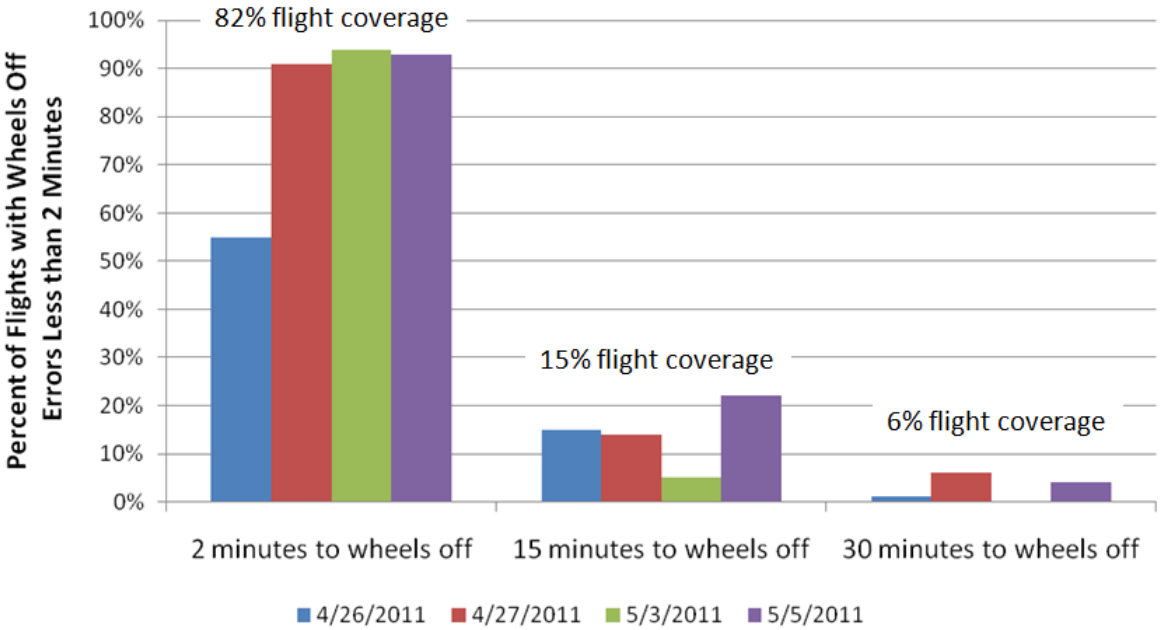


Figure 13: Error in wheels-off times at DFW.

for the flight represented in Figure 15a has a width of about 4 minutes or 60 nautical miles (NM) out. At the same distance away, the 90% prediction interval for the flight represented by Figure 15b is approximately 6 minutes. Thus the ETA for the first flight can be considered more predictable than that of the second flight at a distance of 60 NM from the runway. In fact, the prediction intervals for the first flight generally remain narrower than those for the second flight all the way into the runway, with the exception being at around 30 NM, where the prediction intervals have comparable widths. We believe that a closer examination of the differences between prediction intervals for different flights could lead to valuable operational insights and suggest the inclusion of new predictor variables that could improve model accuracy.

4.4 OPPORTUNITIES FOR IMPROVEMENT

As was mentioned previously, various statistical methods have been used to show improvement in taxi time predictions. However, none of these methods have been tested as part of a fielded system that is designed for real-time operations. To mature these research efforts into a useful capability, we recommend the following:

- Model Improvements
    - Since models have been developed for different airports, a comparative study evaluating the models needs to be done to evaluate performance under different operating environments.

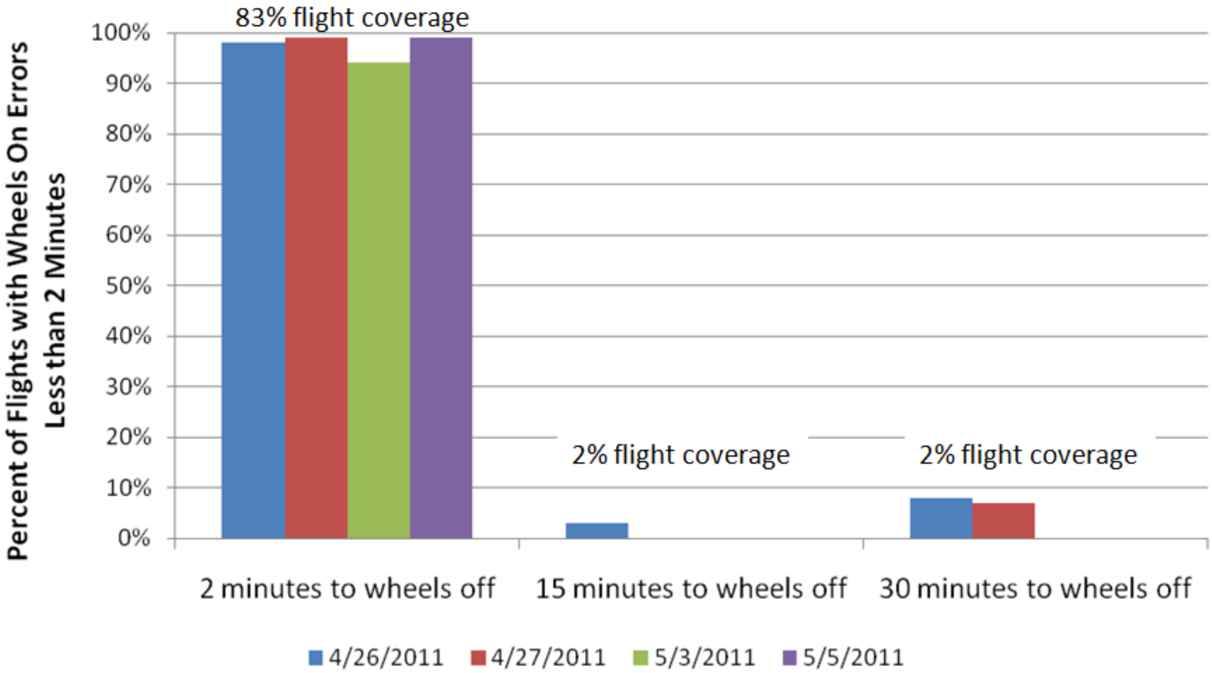
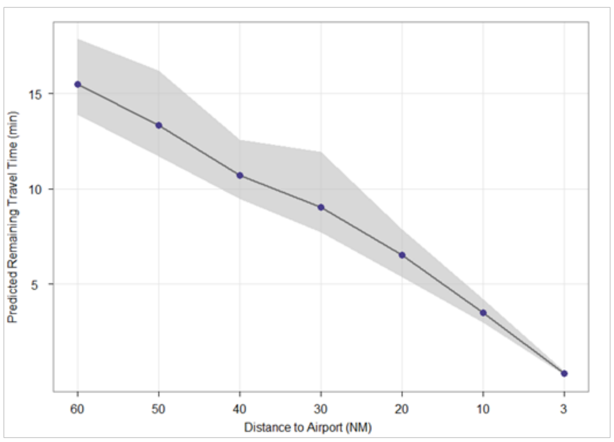


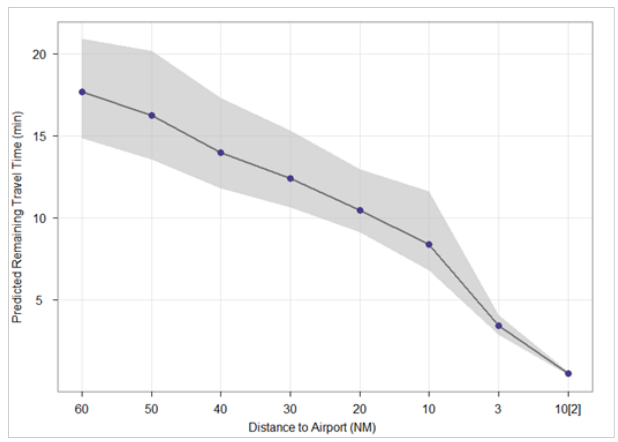
Figure 14: Error in wheels-on times at DFW.

  - As part of the comparative study, evaluating the impact of additional features and their availability on the predictive accuracy of regression-based models is required.

- Integration and Adaptation
  - Modification and generalization of feature sets to be easily adaptable to airports with different characteristics would assist with broader application of this capability.
  - Implementation of these models in a real-time framework such as a TFDM prototype and evaluation of the impact of uncertainties of push-back times, etc., on the accuracy of forecasted taxi time predictions is important for gaining confidence for operational use.
  - Investigation of the impact created by uncertainty in information provided to downstream DSTs (e.g., stochastic runway sequence optimization) is also important for operational readiness.



(a) Flight-A arrival time prediction



(b) Flight-B arrival time prediction

Figure 15: Arrival time predictions for two example flights.

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5. SEQUENCE OPTIMIZATION

5.1 OVERVIEW

Managing departure sequences (and those mixed with arrivals) is one of the more difficult tasks tower controllers have to perform. The proper formation of runway sequences is however critical to maintaining efficiency in surface operations, as well as deriving associated benefits in reduced delays and fuel burn. There are a number of factors that can impact the formation of a correct sequence, including: airport configuration, runway layout, traffic flow constraints, weather impact, wake separation standards. Therefore the sequencing function must integrate inputs from internal functions and external systems such as: surveillance, airport configuration, taxi prediction, ERAM, TFMS, and TBFM. The sequence may also be controlled at different locations on the surface such as: ramp, runways crossing point, or runway queue. Due to the cognitive complexity in accounting for the aforementioned factors, as well as the dynamics of surface operations, human controllers often simply rely on a First Come First Served (FCFS) strategy for sequencing aircraft. An automation based tool for sequencing aircraft is therefore expected to provide significant assistance to controllers in this challenging task area, as well as yielding efficiency benefits.

The goal of aircraft sequencing is to provide controllers a sequence advisory for both departures and arrivals which need to use a given runway so as to improve efficiency of operations while maintaining the required safety. The efficiency is typically measured in terms of average delay or throughput while the safety is governed by the separation requirements between individual flights and the downstream metering constraints such as Estimated Departure Clearance Time (EDCT) restrictions. The minimum separation requirements between aircraft are defined by the aircraft weight category; the departure requirements for a single runway are summarized in Table 2. For example, if a small aircraft leads, then the trailing heavy has to wait 60 seconds before beginning its takeoff roll; however, if the order is reversed, the small aircraft has to wait 120 seconds after the leading heavy departure. The efficiency gains come from potential re-sequencing opportunities when, for example, a small departure is cleared before a heavy, saving up to 60 seconds in delay even if the heavy aircraft is ready to take off earlier.

In the following subsections we discuss: i) a select set of approaches for performing sequence optimization, ii) the algorithm implemented in the TFDM prototype evaluated at DFW, and its performance, and iii) suggested activities for maturing this capability for inclusion into an objective TFDM system. We note that the algorithm implemented in the current TFDM prototype is a slightly enhanced variant of the FCFS scheme. We also observe that, due to relatively low congestion, DFW airport is not a particularly effective operational site for testing the sequencing capability. Therefore, further algorithmic improvements to the sequencing function, as well as better venues for testing this capability would be necessary to pursue for the objective TFDM system.

5.2 STATE OF THE ART

The benefits of runway sequence optimization have been tested only in human-in-the-loop and numerical simulations. Two types of numerical simulations have been proposed: those that compare the benefits of only runway sequence optimization, and those that evaluate the benefits of runway sequence optimization as part of an overall integrated surface optimization strategy. These simulations typically compare the benefits of sequence optimization against FCFS sequences prevalent in today's operations. The benefits of runway sequencing have been shown to increase with the growth of demand and when the aircraft mix is more diverse [35–37]. The following optimization approaches are used in the literature: Mixed Integer Linear Programming (MILP), Dynamic Programming (DP) or Genetic Algorithm (GA) models[1]

TABLE 2: Runway Separation Requirements for Departures (in seconds)

		Trailing			
		Small	Large	Heavy	B757
Leading	Small	60	60	60	60
	Large	90	60	60	60
	Heavy	120	120	90	120
	B757	120	90	90	90

For these algorithms to become operationally feasible two major issues have to be addressed: computational time and impact of uncertainties on the resulting optimization algorithms. While several strategies for dealing with long computational times both for MILP and DP formulations have been proposed in the literature [21, 35, 39], the impact of uncertainty has been addressed only by NASA Ames [40] and Georgia Institute of Technology [41]. For example, Balakrishnan and Chandran developed a polynomial time dynamic programming algorithm which schedules runway operations while limiting the number of positions an aircraft can shift from its FCFS position [35]. However, the effect of uncertainties associated with push-back times, wheels-on times and taxi predictions have not been explicitly considered by their algorithm.

The NASA Ames approach is a two-stage optimization algorithm described in [42] which consists of (1) the Spot Release Planner (SRP) that provides sequence and timing advisories to the tower controller for releasing departure aircraft into the movement area to reduce taxi delay while achieving maximum throughput, and (2) the Runway Scheduler which provides take-off sequence and arrival runway crossing sequence advisories to the local controllers to maximize the runway usage. Note that this approach effectively combines runway sequence optimization and departure metering of individual flights which is described in Section 6. The combined strategy is referred to as Spot and Runway Departure Advisory (SARDA). SARDA was tested in human-in-the-loop simulations of Dallas/Fort Worth International Airport and exhibited a reduction in average departure delay, number of aircraft stops in the movement area, fuel consumption and engine emissions when compared to performance under current operating procedures [37]. While the stochastic effects are not explicitly incorporated into the modeling framework, the authors claim that the two-stage

[1]A comparison of GA and MILP approaches is available in Ref. [38], while a paper by Balakrishnan and Chandran provides an overview of the DP approaches [35].

approach with multiple planning horizons used by the SRP algorithm mitigate the effects of uncertainties inherent in airport operations. They have also published a simulation-based study which shows that the sequences produced by the deterministic Runway Scheduler consistently outperform the FCFS sequences when uncertainty is introduced into aircraft taxi times [40].

Uncertainty is included explicitly in the runway sequence optimization algorithm by Solveling et al. [41]. They approach the stochastic runway planning problem in two stages. First, the stochastic optimization algorithm finds the weight class sequence that maximizes throughput while simultaneously achieving a desirable sequence for the second stage. In the second stage, once uncertain parameters associated with runway departure and arrival times are realized, a deterministic MILP algorithm is used to assign individual aircraft to positions in the weight-class sequence obtained in the first stage. The computational results using Detroit Metropolitan Wayne County Airport (DTW) data show that the planning algorithm reduces average flight delays over those of the FCFS policy when combined arrival and departure rates are high compared with runway capacity. The runtime of the algorithm is suitable for real-time implementation with execution time of $O(1)$ minute, while it is meant to be executed every 15 minutes. As opposed to the SARDA algorithm above, this approach has only been tested in computer simulations and more research needs to be done on coupling of the two optimization problems and regarding some of the modeling assumptions, like assuming departure/arrival times are statistically independent.

In general, the probability distributions used by [40] and [41], while representative of the airport operations considered, do not come from the actual distributions achieved in the field. A Sensis Corporation publication [43] quantifies several sources of uncertainties present in airport surface operations including ramp spot wait time uncertainties, taxi route uncertainties, taxiway transit speed uncertainties, and uncertainties associated with switching departure queue during runway configuration changes. The primary sources of uncertainty for runway sequence optimization are push-back times, taxi times and wheels-on times for arrivals. A taxi prediction modeling framework based on Quantile Regression Forests [26] can be used to provide predictions of the probability distributions associated with each individual prediction. In particular, the framework allows for estimating the mean and median times for a given flight as well as quantiles of the distribution and prediction intervals which provide natural bounds for the stochastic optimization algorithms as used by Solveling et al. [41].

As exemplified by the SARDA algorithm described above, which combined runway sequencing and departure metering, it is difficult to isolate sequence optimization from other airport surface management techniques. In SARDA, the runway sequencing algorithm assumed that the earliest runway availability time can be accurately forecasted. An alternative strategy is to combine runway sequencing with taxi route assignment as part of an integrated optimization strategy. Here are the integrated surface optimization components typically considered in the literature [21, 23]:

- Airport Configuration: selects runway configuration sequence and the time of configuration change to maximize airport capacity given demand, weather and other constraints
- Runway Routing: assigns routes to flights within the terminal area to minimize emission costs
- Runway Assignment: assigns individual flights to runways

- Runway Sequencing: maximizes runway throughput by taking advantage of the separation requirements between individual flights and their required slot assignments
- Taxiway Planning: provides a gate holding strategy which controls gate push-back time to create conflict-free surface trajectories and reduce fuel burn
- Gate Assignment: provides gate assignments to minimize ramp congestion

These algorithms are not yet mature enough for operational deployment.

5.3 TFDM PROTOTYPE CAPABILITY

Benefits assessment of two types of optimization strategies has been performed at DFW airport with current and potential future traffic levels[2]. The problem formulation adopted for the TFDM benefits assessment application for optimizing aircraft sequences is largely based on the SARDA approach described above. Two types of sequence optimization strategies were analyzed. The first one is a basic runway sequencing version which would provide take-off and runway crossing sequencing advisories to the Local Controller for aircraft already at or near the departure runway. Because aircraft are to be sequenced at the runway, it was assumed that at least two sub-queues were available for departure re-sequencing. The second type of sequence optimization (referred to as advanced optimization) provides an advisory to the Ground Controller for gate release times of individual departures. At the core of both methods is an optimization program that minimizes a given objective function by scheduling the runway entry times for departures and arrivals while taking into account the separation needed between individual flights and the required time windows for individual departures. Both algorithms assume that the controllers will adhere to the minimum separation requirements between the aircraft and to the minimum observed times for the separations between departures and arrivals . The second algorithm also assumes that the departures can take their delay at the gate resulting in reduced fuel burn and unimpeded taxi time travel to the runway. The algorithm also assumes that the departures are able to maintain the appropriate speed so that their taxi times are equal to the times used by the algorithm (e.g., typical unimpeded times). In such a case, the gate release sequence would produce the desired runway entry sequence and no secondary optimization for the Local Controller would be required.

The following measurable benefit metrics were evaluated between the optimized and baseline behaviors:

- The potential delay savings.
- Fuel burn savings due to delay savings. For the advanced sequencing version, additional fuel burn savings are achieved since departure delay is absorbed at the gate instead of waiting in the active movement area. Note that for the case study of DFW these additional gate-hold fuel burn savings were not included because the aircraft are typically held at the spot with engines on.

[2]The detailed explanation of the methodology and interpretation of the results is available in the TFDM benefits assessment report [36]

The potential sequencing benefits were calculated for a runway configuration exemplified by DFW departure runway 17R and crossing arrivals from 17C and 17L. The baseline model was derived using the taxi time models described in Section 4 and FAA forecasts were used for demand projections in the future. According to the forecasts, the demand at DFW grows as follows 2010:2015:2020:2025:2030 = 1.0x:1.1x:1.2x:1.3x:1.5x. We assume that capacity remains the same over this time period. The demand projections were available in 5-year increments and the resulting daily delay savings due to both basic and advanced sequence optimization versions are summarized in Figures 16 and 17. The benefits of basic sequence optimization are smaller because they only come from re-sequencing of the aircraft given the minimum separation requirements whereas advanced sequence optimization allows for reduction of taxi times due to unimpeded travel if the delays are taken at the gate/spot.

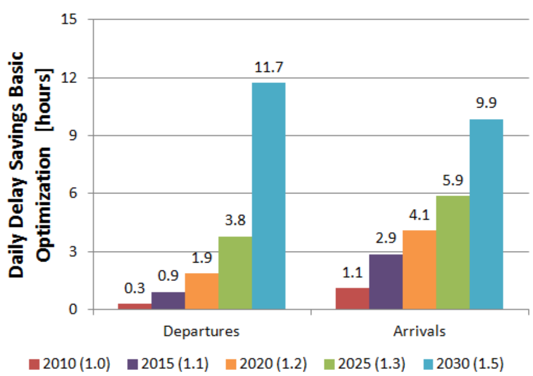

Figure 16: Basic sequence optimization: future year benefits at DFW.

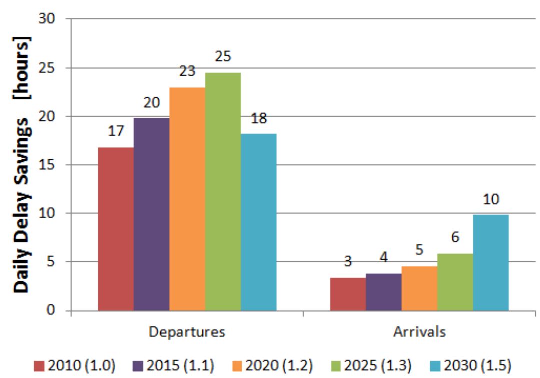

Figure 17: Advanced sequence optimization: future year benefits at DFW.

At DFW few opportunities exist to be more efficient by sequencing compared with FCFS operations because more than 90% of aircraft at DFW are classified as *Large*. Parametric analysis was performed to explore re-sequencing benefits by artificially varying the aircraft fleet mix so that the results of the benefits analysis could be extrapolated to other airports. As the results in Figure 18 show, the benefits increase substantially if the fleet mix is more diverse, because runway re-sequencing optimization can fix more FCFS inefficiencies. The fleet mixes considered in the simulation are as follows and represent the current-day fleet mixes at DFW (Fleet Mix I), SFO (Fleet Mix II), and JFK (Fleet Mix III): see the table in Figure 19.

5.4 OPPORTUNITIES FOR IMPROVEMENT

Both the advanced and basic versions of sequence optimization described above require accurate predictions of unimpeded taxi times, push-back times and wheels-on times for arrivals. For example, basic sequence optimization needs a forecast of aircraft runway ready times to perform optimization on a selected time interval. In addition, the advanced version requires that the de-

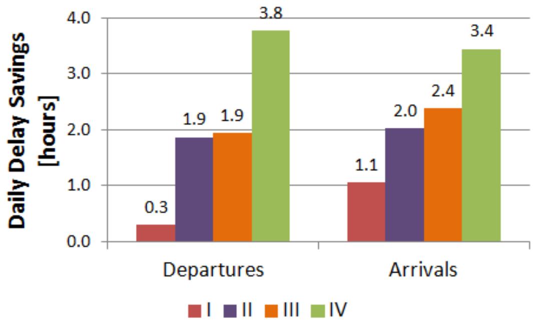

Figure 18: Effect of varying fleet mix on basic sequence optimization for 2015 demand levels.

Fleet Mix	Small	Large	Heavy	B757
I (~DFW)	1%	90%	4%	5%
II (~SFO)	15%	60%	15%	10%
III (~JFK)	2%	60%	29%	9%
IV (uniform)	25%	25%	25%	25%

Figure 19: Fleet mix categories used for basic sequence optimization.

partures are able to hold at the gate and then travel unimpeded to the runway. It is important to note that the types of accuracies required by deterministic optimization described above have not yet been achieved by the tools in the field. In order to make sequence optimization algorithms work in an operational setting, several research avenues should be pursued. First, better models for taxi times, push-back times and wheels-on times should be developed. Second, stochastic optimization techniques need to be used so that the uncertainty associated with those times is explicitly modeled. Otherwise, given the uncertainty present in the input parameters, the majority of the estimated benefits due to deterministic sequence optimization might be difficult to realize in the field. Since the stochastic effects which would be present in the actual operational environment were not explicitly modeled here, the delay savings presented above provide an upper bound on potential sequencing benefits. Lastly, sequence optimization should not be considered in isolation since other decision support tools, like runway assignment and taxi routing, have a direct impact on the input variables of the sequencing algorithms.

6. DEPARTURE METERING

6.1 OVERVIEW

Queues of aircraft at the end of departure runways ensure that there is a constant supply of aircraft for controllers to select for release and, hence, make full use of departure runway capacity. However, only a certain number of departing aircraft are required in the queue to ensure that high throughput is achieved (with this number depending on airport and operations-specific variables). When this number is exceeded, there is unnecessary additional congestion on the surface, leading to increased taxi-out delay and excessive fuel burn and emissions without any operational advantage.

One mechanism for regulating how many aircraft enter a departure queue is to throttle the number of aircraft pushing-back or leaving the non-movement ramp area in a given time period. Departure metering processes attempt to manage push-back operations and, thereby, avoid releasing aircraft onto the taxiways until they can be efficiently accommodated at the runways, while simultaneously maintaining high departure throughput. This effectively shifts taxi-out delay to the gate or ramp areas (preferably with engines off), resulting in benefits such as reduced fuel burn and emissions, increased passenger and bag connectivity, and more predictable taxi-out times. This capability is consistent with capability SS17 specified by the Surface Technical Team Working Group [14].

- [SS17] *Manage departure queue length* - The departure queue is to be managed through aggregate allocation of the number of flights that can enter the movement area to flight operators during a specific time interval – conducted on a runway-by-runway basis

The departure metering capability can be implemented in a number of ways (as will be explained in the following subsection) depending on the specific operational conditions at an airport, e.g., i) using gate or spot metering depends on whether push-backs are controlled by the main FAA tower or airline ramp towers, ii) with or without airline coordination depends on airline data availability, iii) using aggregate or runway specific metering depends on the physical characteristics of the airport, and iv) application of individual or batch flight metering is impacted by whether there is a dominant carrier or not. Departure metering can be improved by information available from other TFDM capabilities (and in turn improve the delivery of benefits from those tools), for example recommended departure sequences coupled to improved taxi-time models can be used to inform proper aircraft push times of specific aircraft. The departure metering capability is not in common use for present day operations due to factors such as: i) an effective implementation of even the simplest variant of this capability requires airport-specific characteristics to be carefully modeled, and ii) some sort of decision aid is typically required for operational use. For these reasons, and due to the significant benefit offered by this capability and the relative maturity of some of the algorithmic concepts to deliver benefits, departure metering is considered an important candidate for inclusion in an automated decision support system.

The following subsection describes some of the candidate approaches for implementing departure metering. The approach initially implemented within the TFDM prototype was one that did not rely on airline coordination given that, at the time, we did not have direct access to airline data at the DFW test site. The type of traffic mix at DFW, as well as the state of taxi time predictions in the current TFDM prototype implementation allowed only limited evaluation of this capability. More effective testing of this capability would be possible at an alternate airport, and in a high fidelity simulation environment. It would also be useful to compare the effectiveness of this approach with other alternative approaches. Activities for additional evaluation and maturation of this capability are discussed further in the final subsection.

6.2 STATE OF THE ART

Several implementation options to achieve the principles described above have evolved: aggregate traffic metering using a push-back rate, metering groups of flights, and metering individual flights:

- Aggregate traffic metering using push-back rate: recommend a push-back rate to ATC, who then determine which flights to clear to push consistent with this rate. This approach has the benefit of achieving some level of departure queue management with minimal real-time airline coordination and automation needs, but with lower levels of control as a result. An approach falling into this category is the "Push-back Rate Control" concept being explored by MIT with recent field trials at Boston Logan Airport [Simaiakis et al. (2011)]. This type of metering can generally be achieved with minimal access to airline-specific information.
- Metering groups of flights: recommend a maximum number of flights to release from a given ramp area in a certain time interval. This approach is attractive because it provides an equitable allocation of departure capacity to each flight operator who are then empowered to choose which specific flights to release given internal priorities. An approach falling into this category has been developed, evaluated, and continues to be refined by FAA/STBO (Collaborative Departure Queue Management (CDQM) [Brinton et al. (2011)], demonstrated at Memphis and Orlando airports). This type of metering requires at least some level of real-time airline collaboration to allow dissemination of the recommended number of aircraft to allow to push from each carrier.
- Metering individual flights: recommend when specific flights should leave from the gate or spot. This approach is attractive because in theory departure metering can be combined with efficient departure sequence generation in order to maximize benefits potential. However, it requires significant real-time airline coordination to know when flights will be ready to push-back, as well as effective implementation of an arbitration strategy when the number ready to push exceeds the number that should be allowed to push. Approaches falling into this category are being developed by NASA Ames (Spot and Runway Departure Advisory (SARDA) [Hoang et al. (2011)]); FAA/STBO (Collaborative Departure Scheduling (CDS) [Brinton et al. (2011)]) and PASSUR Aerospace (who have been conducting field trials recently at New York JFK Airport) [Nakahara et al. (2011)].

The different approaches suggested by the categories outlined above can actually be considered as simply different implementation strategies to achieve the same objective of surface congestion management. At the core of all the methodologies is the objective to limit the development of surface congestion. This can be captured in the concept of throughput saturation curves illustrated in Figure 20, which relate departure throughput to an appropriate traffic metric (e.g., the number of departing aircraft on the airport surface or in a departure queue). All of the implementation approaches described above can be characterized by this type of curve. As more aircraft push-back from their gates onto the taxiway system, the throughput of the departure runway initially increases because more aircraft are available in the departure queue. But as the number of aircraft continues to increase, the airport eventually reaches a saturation departure rate. The saturation value depends on the airport configuration, arrival demand and meteorological conditions (VMC/IMC) as well as other airport conditions and human factors considerations. Beyond the saturation point, any additional aircraft that push-back simply increase the time they are taxiing out with engines on without any gain in departure rate. The objective of departure metering is to maintain the number of aircraft pushed-back at a certain control level just above the saturation point. In this way, high departure throughput can be achieved without unnecessary surface congestion and the resulting excess delays and fuel burn.

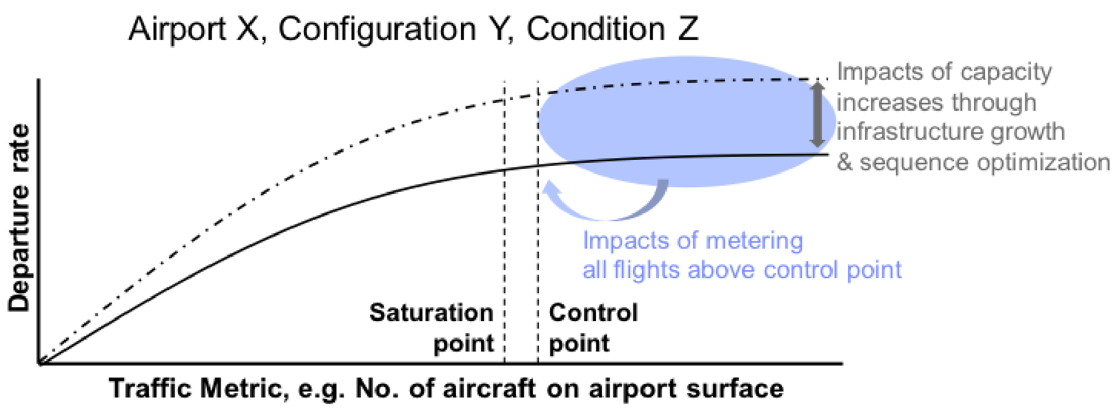

Figure 20: Throughput Saturation Curve.

TFDM benefits assessment activities conducted by MIT Lincoln Laboratory have undertaken a detailed assessment of departure metering at a broad set of airports (OEP35), now and into the future (to 2035) [Nakahara (2012)], and the throughput saturation curve concept was a cornerstone of this work. But in order to overcome the uncertainties and difficulties inherent in future system forecasting, this work developed a novel multi-fidelity modeling approach and proposed three methods for estimating the benefits of departure metering where the higher fidelity models study a subset of airports to inform and validate the lower fidelity models used on the entire set of airports. In the highest fidelity model, a detailed analysis of a field trial of departure metering at JFK airport was conducted using current operational data. The medium fidelity models estimated the benefits of implementing departure metering at 8 major US airports from 2010 to 2030 by simulating congestion and performance levels through taxi time estimation. The lowest fidelity models explored several options for generalizing the results to the OEP35 airports. The results were also validated against historical benefits estimates as well as field trials of departure metering where available. The findings showed that SCM was estimated to result in fuel savings on the order of 1% of the total fuel burn in all stages of flight and between 5% and 45% of taxi-out fuel burn, depending on the airport. Across the 2015–2035 timeframe at the OEP35 airports, fuel savings from departure metering were estimated to be in the range of $3 to 9 billion. Additional benefits, for example due to increased passenger and bag connectivity, have yet to be fully quantified, but would be additional to these fuel savings.

6.3 TFDM PROTOTYPE CAPABILITY

The discussion in the previous section illustrates that there is significant benefits potential from departure metering DSTs and, compared to other DST areas, the algorithms are relatively mature and undergoing field trials in different forms at various sites. This benefits potential and relative algorithmic maturity was the reason why MIT Lincoln Laboratory fielded a preliminary TFDM prototype departure metering capability for the DFW field trial which was then planned to be refined and extended for a follow-on evaluation (which ultimately did not take place). Although DFW is not a benefits-rich airport in terms of departure metering (MIT Lincoln Laboratory benefits assessment described above estimated DFW to have one of the lowest needs for departure metering among the OEP35 because it has few periods of high surface congestion), this prototype capability was designed to:

- Explore how a departure metering capability might be integrated into the TFDM system
- Gain user feedback on the prototype capability in shadow-mode operations
- Gain insight into implementation issues given DFW layout, procedures, etc. to add to operational knowledge from other field site activities which could be leveraged for adaptation of TFDM to multiple sites

The specific algorithm deployed at DFW used a variant of the BOS N-Control algorithm which, instead of being designed to manage the total number of taxiing aircraft on the airport surface (as was used at Boston), was instead designed to maintain the number of aircraft in the departure queue for the main east side departure runway at any given time to below a target number. This modified approach was termed "Q-Control" to distinguish it from the N-Control algorithm and was found to be more appropriate for DFW implementation because of the airport's operating characteristics. The departure metering algorithm used projected departure demand (from the SDSS timelines) and taxi time models to predict the size of the departure queue at one minute intervals 10–20 minutes into the future. If the queue size was estimated to exceed a target number (set to six for the DFW trials based on extensive analysis) for more than seven of the minutes in the 10–20 minute interval, a recommended spot release rate was calculated that would reduce the estimated queue size to below the target number. This recommendation was shown on the ground controller's TFDM/FDM display, as shown in Figure 21.

The follow-on implementation at DFW had planned that American Airlines would supply requested push-back times for their flights, and this would be used to calculate recommended push rates for each specific ramp area at DFW. This recommendation could then be shown to the ramp controller who could actually hold the aircraft at the departure gate, but this development and implementation did not occur because the follow-on live trial was cancelled.

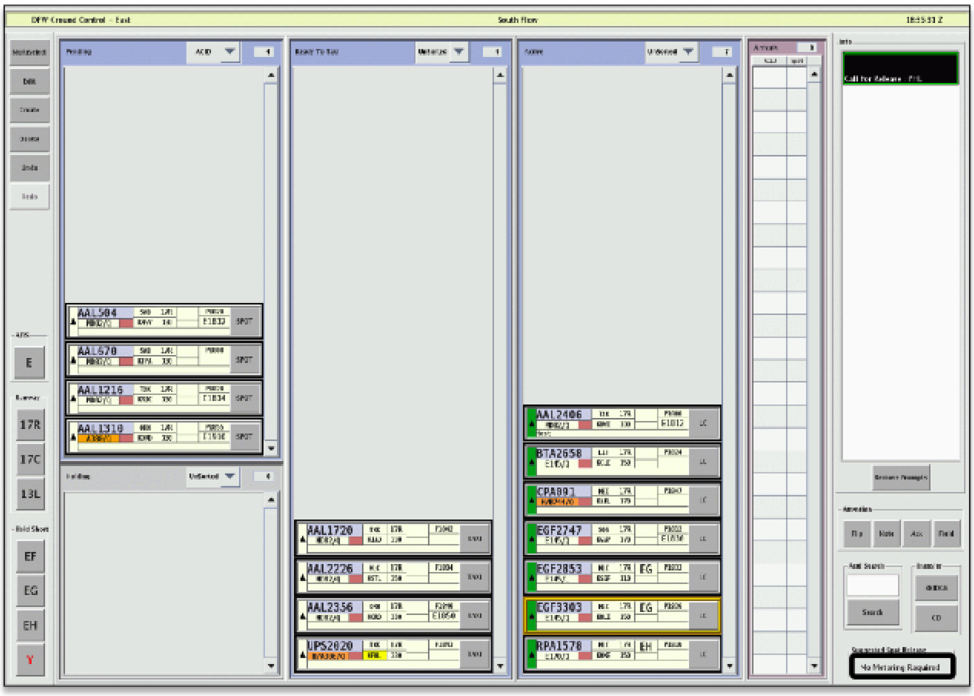

Figure 21: DFW Departure Metering Prototype on TFDM Flight Data Manager Display.

The performance of the DFW prototype capability was reported in the DFW final report [11]. Figure 22 shows the SDSS-estimated queue size for runways 17R/35L over the entire DFW trial period. The estimate only exceeded the departure queue size threshold of six flights on two occasions: at 20:29 UTC on 25 April 2011 and 12:23 UTC on 4 May 2011. For the second event, the estimated queue size exceeded the threshold for only one minute and hence was not sufficient to trigger any metering recommendations, which required the threshold to be exceeded for at least seven of the one-minute intervals between 10 and 20 minutes into the future. However, this criterion was met for the first event, as shown in Figure 23.

At 20:29 UTC, the metering algorithm used the SDSS-estimated queue length for 10 minutes in the future, at which point it exceeded the metering threshold. It then used the estimated queue size for 10–20 minutes into the future and determined that the estimated queue size exceeded the threshold for more than seven minutes in that interval, and hence issued a metering recommendation for 0 aircraft per five minutes to be released from the spot until the queue size

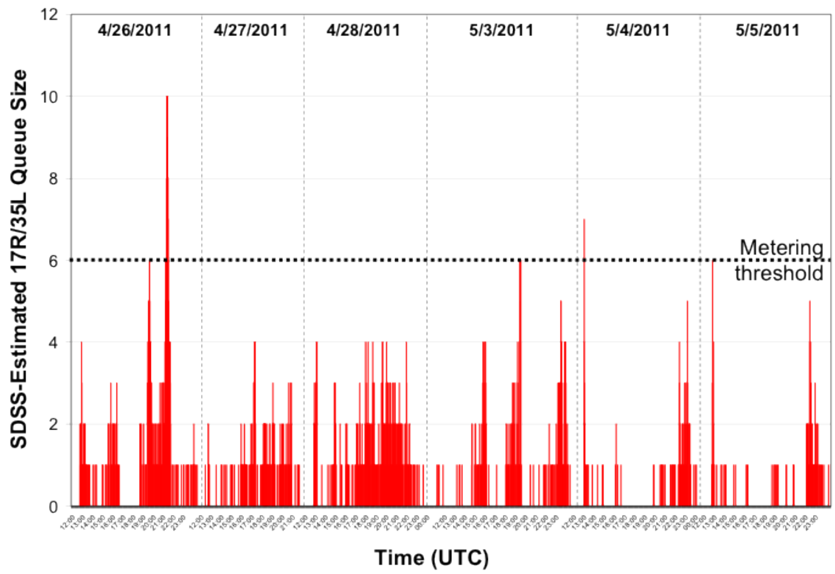

Figure 22: Estimated Queue Sizes for DFW Runway 17R/35L.

was estimated to drop below the threshold. Examination of the DFW trial logs show this metering recommendation was properly issued and cancelled five minutes later. These data show that the TFDM prototype departure metering algorithm worked as designed given the estimated departure queue sizes. However, further analysis of the ASDE-X surveillance data showed that there were several other instances during the DFW trial when the actual queue sizes exceeded the threshold number for a long enough period to warrant metering recommendations, but the estimated queue sizes were too low. An example of this is shown in Figure 24: the metering threshold (the black horizontal line at y=6) was exceeded at around 13:18, but the SDSS estimate of queue length made at 13:12 was well below the saturation level.

Thus, the metering algorithm passed the DFW trial success criterion in that it worked properly given the inputs available to it, but queue size estimate inputs need to be significantly improved for the metering recommendations to be accurate relative to the actual operation.

6.4 OPPORTUNITIES FOR IMPROVEMENT

There are numerous opportunities for improvement of the implementation and assessment of departure metering capabilities to build upon the state of the art and the basic capability implemented at the TFDM DFW field demonstration outlined above. These recommended improvements include:

- Developing refined departure metering algorithms. This could include taking advantage of other inputs potentially available via TFDM (e.g., improved demand estimates, taxi-time

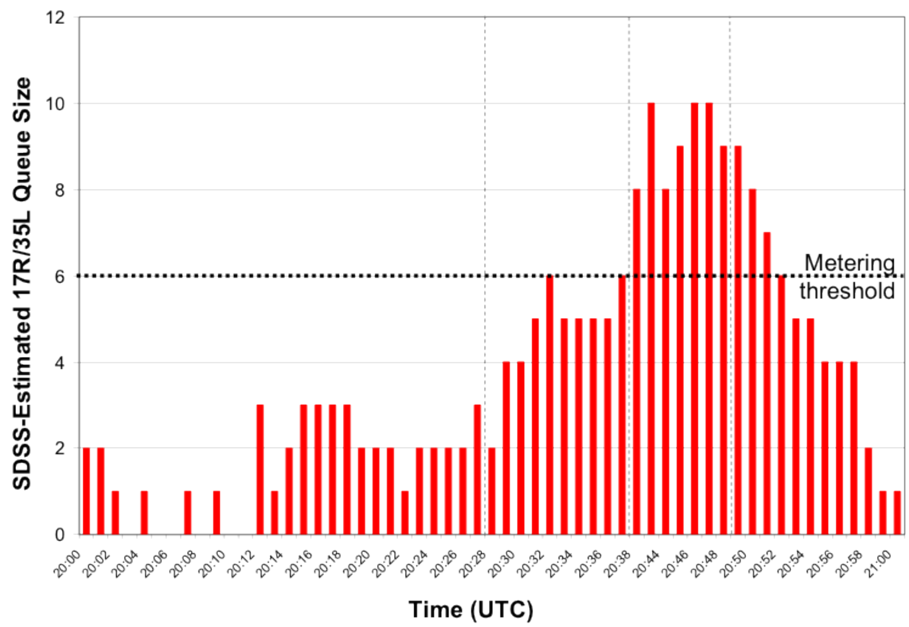

Figure 23: Estimated Queue Sizes for DFW Runway 17R/35L, 5/4/2011 at 12:23 UTC.

models, recommended departure sequences, etc.) and assessing the incremental benefits of access to this data at a variety of different types of airports.

- Exploring adaptation challenges. This could include identifying what aspects of departure metering algorithms and their implementation vary by airport, and then undertaking specific tailoring of departure metering algorithms and implementation strategies at specific airports to support the delivery of benefits from the capability at a wide range of airports. Further development and testing of a TFDM prototype capability. This could include testing appropriate refinements to departure metering implementations within the TFDM architecture at benefits-rich airports using field trials, human-in-the-loop simulation and/or fast-time modeling to help refine human acceptance and benefits assessment activities.

Given the high benefits potential and relative maturity of the departure metering capability, these suggested improvements are strongly recommended to help deliver significant benefits from TFDM and other future integrated DST systems.

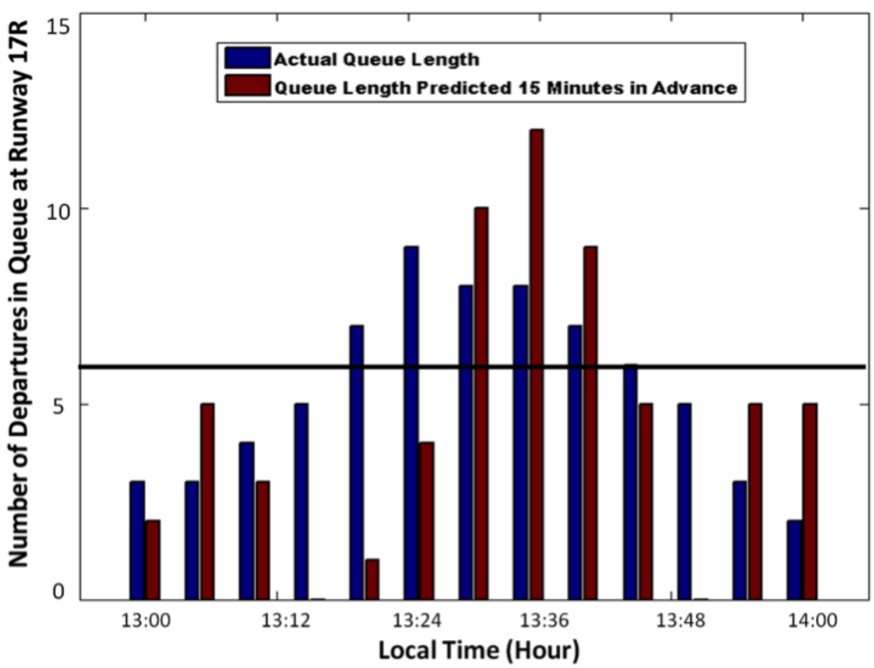

Figure 24: Actual versus Estimated Queue Sizes for DFW Runway 17R/35L.

7. DEPARTURE ROUTING

7.1 OVERVIEW

The efficiency of departure operations on the surface can be compromised when departing aircraft (especially ones in a runway queue) encounter blockages on their filed routes, are unable to meet departure time constraints (such as EDCTs), or are unable to exploit available time slots in an overhead flow. It is common to find operational scenarios where the inability to adequately respond to convective weather can result in route blockages for head-of-line aircraft in a queue. This can cause delays for the impacted aircraft, along with other aircraft in the queue that may have clear routes. A similar situation can result if aircraft near the head of a queue are unable to meet their constrained departure times. In order to mitigate inefficiencies resulting for conditions similar to the aforementioned scenarios, improved automation tools are needed in the tower, as well as in some of the collaborating facilities.

The need for tactical decision support in the terminal environment to complement strategic approaches for assisting operations during convective weather periods has been noted by Evans [44]. This need can result from the higher uncertainty associated with making longer term strategic predictions about the state of weather, and its impact on traffic in terminal environments, especially those with historically higher traffic density. Strategic planning provides limited assistance for flights whose duration is short (about one hour). The needed tactical decision support requires improved prediction accuracy for traffic operations and weather within the time duration of one hour prior to departure, as well as robust collaboration tools for decision making with tower, terminal, en route, and flight operator facilities. The ability of controllers to implement effective mitigation solutions to routing problems in the tactical terminal environment requires development of algorithms that provide operationally suitable robust routes.

The following sub-sections describe the work performed as part of the TFDM prototype development effort on departure routing, as well as suggesting additional efforts needed in maturing concepts, algorithms, and interfaces (machine and human) for delivering near-term benefits. In particular we note that the concept of departure routing requires further coordinated maturation and validation through collaborative multi-facility simulations or evaluations.

7.2 STATE OF THE ART

The development of departure routing concept for TFDM has been guided by the recognized need for a tactical decision support capability and the recommendations of an FAA chartered group – Surface Technical Team Working Group (STTWG). The concept design for departure routing in TFDM was guided by the capabilities specified by the STTWG [14]. The primary capabilities considered in the concept were DR01, DR02, DR03, and DR04. These capabilities, as originally published, are reproduced below (although some of these have been modified since the original technical team completed its work).

- [DR01] *Display flight-specific departure route indicator* - This capability is the display to controllers of the evaluation performed by DR03 and DR02. An interface is provided for manually re-routing and/or applying tactical surface delays in accordance with weather and traffic flow constraints. While the TFM timeframe is strategic, the tower timeframe is tactical (after pushback). When problems occur in the current route in the tactical time frame, the tower needs to find a new route/solution to the problems.

- [DR02] *Evaluate acceptability of alternate departure trajectories and provide for trajectory change* - This capability extends the strategic (+45 minutes prior to departure) re-routing function of Concept SEVEN [45] (which has been succeded by CTOP [12] into the tactical timeframe (any time prior to departure) and expands the set of routes considered from a pre-coordinated static set (in DR03) to any route submitted by flight operator.

- [DR03] *Evaluate pre-coordinated routes for acceptability relative to weather and traffic flow constraints* - A set of pre-coordinated departure routes is developed for each TFDM airport. Flight operators send ranked subsets of routes each flight can fly. These routes are then evaluated for weather and traffic flow constraints, which may result in re-routes and/or ground delay. Use weather data provided by RAPT, IDRP, TFM to determine if it impacts departure route and display to tower personnel. Includes things such as whether or not flight can avoid weather, using flight specific aircraft performance models.

- [DR04] *Share general route viability assessment and individual flight re-routes and ground delays with flight operators* - For each route, a general assessment of weather impact, Traffic Management Initiatives, and departure delay predictions are shared with flight operators to facilitate shared situational awareness. In addition, re-routes and ground delays generated by DR03 and DR02 for individual aircraft are electronically communicated to flight operators.

Following these capability definitions, the concept development and prototyping efforts for TFDM have focused on a design which leverages existing investments by the FAA related to departure management. In particular our design of departure routing has considered the: i) Route Availability Planning Tool (RAPT), ii) Departure Flow Manager (DFM), iii) Collaborative Trajectory Options Program (CTOP) and iv) Integrated Departure Route Planner (IDRP). These systems provide key information to TFDM for the departure routing function, such as: i) weather constraints, ii) traffic constraints, iii) flight operator preferences, and iv) potential alternate routes. The collaborative decision making concepts employed by these systems have also guided the operational concept and interface design for TFDM's departure routing capability.

7.3 TFDM PROTOTYPE CAPABILITY

Advances that were part of the TFDM prototype effort can be categorized into two areas: i) concept development and exploratory implementation, and ii) implementation for field evaluation.

We begin by describing the first category of concept development. The departure routing concept developed for TFDM is aimed at providing viable departure routes and times for flights. The concept focuses on departure decision making in the tactical time frame, while considering strategic constraints that may arrive from en route traffic management or from flight operators. An architectural view underlying the departure routing concept is shown in Figure 25. This architectural view illustrates a collaborative decision making construct in which constraints related to en route traffic and weather are provided by TFMS. Terminal area traffic constraints are derived from TBFM or other terminal area automation, and preferential constraints are derived from the flight operators. Within the time period of TFDM prototype development we have considered available automation systems such as RAPT and DFM to serve as representatives for capabilities that are envisioned to be components of TFMS and TBFM. For evaluation purposes RAPT and DFM were adapted for DFW airport and interfaced with the TFDM prototype. This system integration allows for weather constraint data to flow from RAPT in the form of blockages on departure routes from the host airport. Traffic constraint data is obtained from TFMS for flights impacted by Traffic Management Initiatives and Ground Programs. Additional traffic constraints impacting the terminal environment are obtained from DFM in the form of unavailable time slots for flows that cross established flow constrained areas, and impacted flights that require release times. The constraint information from external automation systems such as RAPT and DFM is integrated by the TFDM departure routing decision support module and correlated with individual flights that are scheduled for departure. The departure routing decision support module also interacts with other internal modules such as the sequencing and scheduling module to establish predicted flight departure times from the assigned runway. The impact of traffic and weather on a pending departure flight along the filed and alternate viable routes is also determined. In this concept, the information about alternate viable routes is determined through coordination with TFMS and flight operations centers. A display concept for the departure routing function has been developed in accordance with the

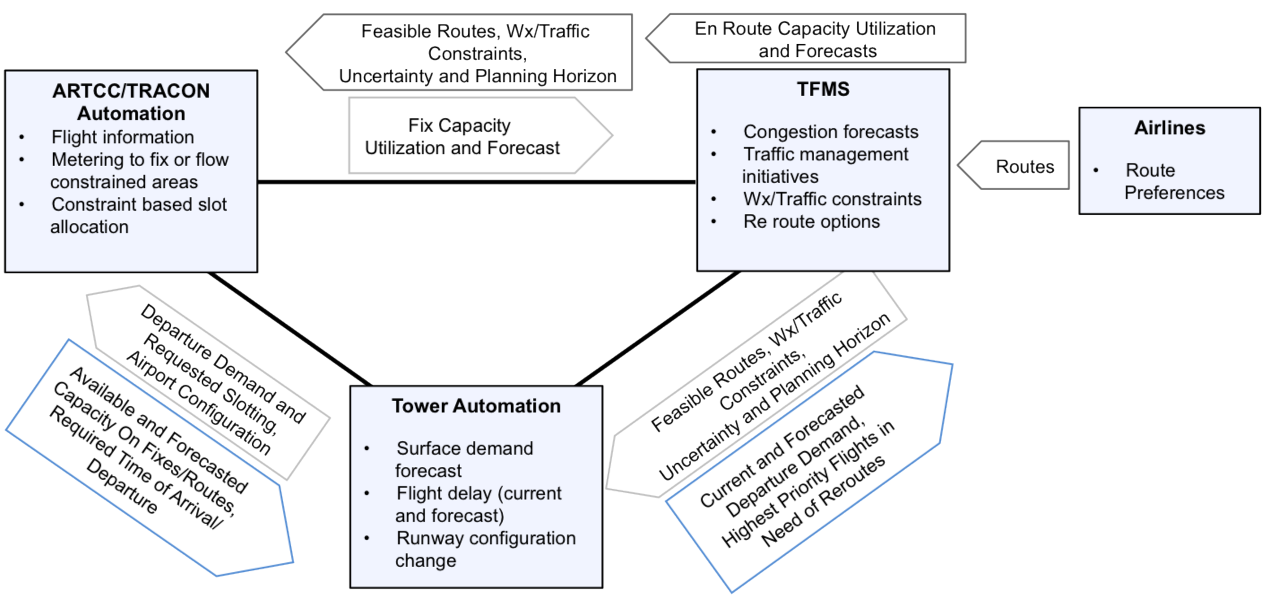

Figure 25: Collaborative Decision Making For Departure Routing.

DR01 capability. The display concept includes two screens illustrated in Figures 26 and 27. Figure 26 provides a situational awareness screen that combines features of RAPT and DFM displays. This screen shows the forecasted weather picture and blockages, along with pending departures impacted by traffic management initiatives which require release times. Figure 27 shows a screen that provides the tower traffic manager with situational awareness pertinent to pending departures such as weather impact, traffic constraints, and forecasted departure time for a set of selected runways and out going routes. This screen also allows the tower traffic manager to collaborate with en route facilities on establishing release times for flights, as well as making re-route decisions. In addition to the decision information provided to the traffic manager, departure routing related information is also propagated to the Ground Control or Local Control positions for the flights whose departure route or time has been impacted. This display concept and the underlying functional capabilities have been developed iteratively with inputs from experienced FAA controllers.

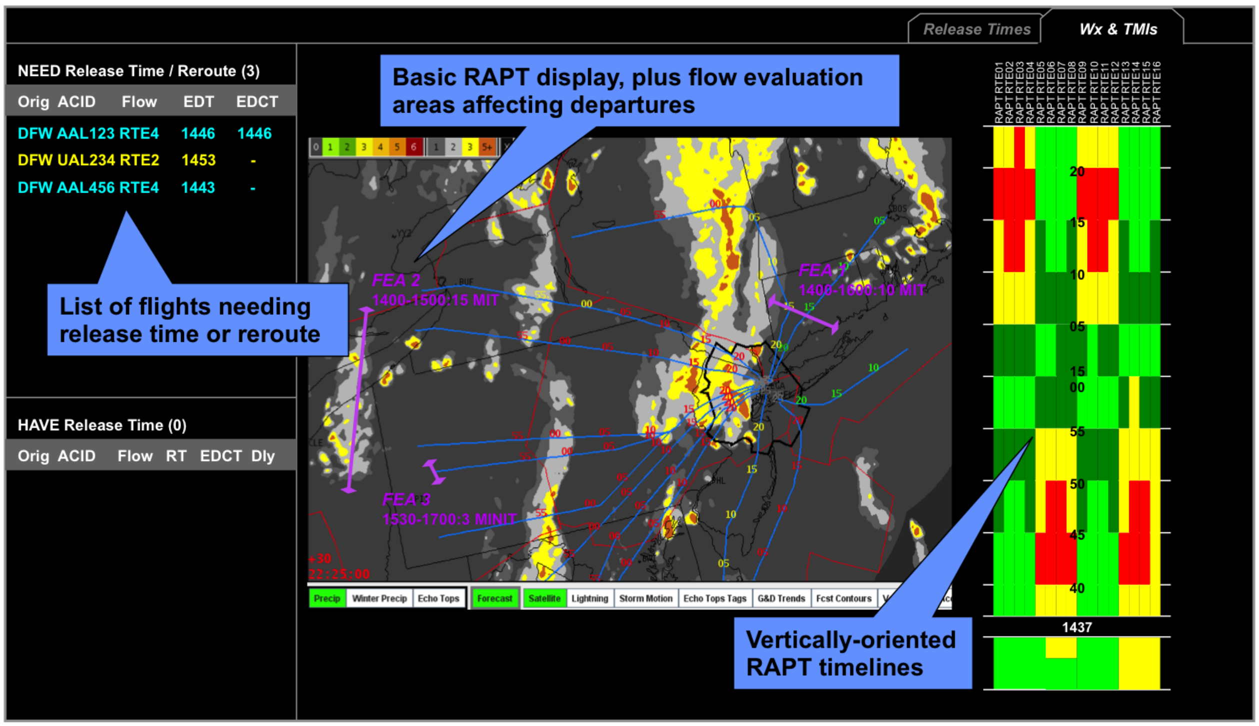

Figure 26: Departure Routing Situational Awareness Display Concept.

The departure routing functional and display concepts developed as part of the TFDM prototype effort provide a foundation for capabilities DR01-04. A number of computer-human-interface, software and algorithmic elements needed to support these capabilities (a part of exploratory implementation) were implemented in the TFDM prototype software. However, due to time and scope constraints associated with the TFDM demonstration conducted at DFW in April 2011, a limited version of the departure routing concept was fielded. The capabilities implemented for our second

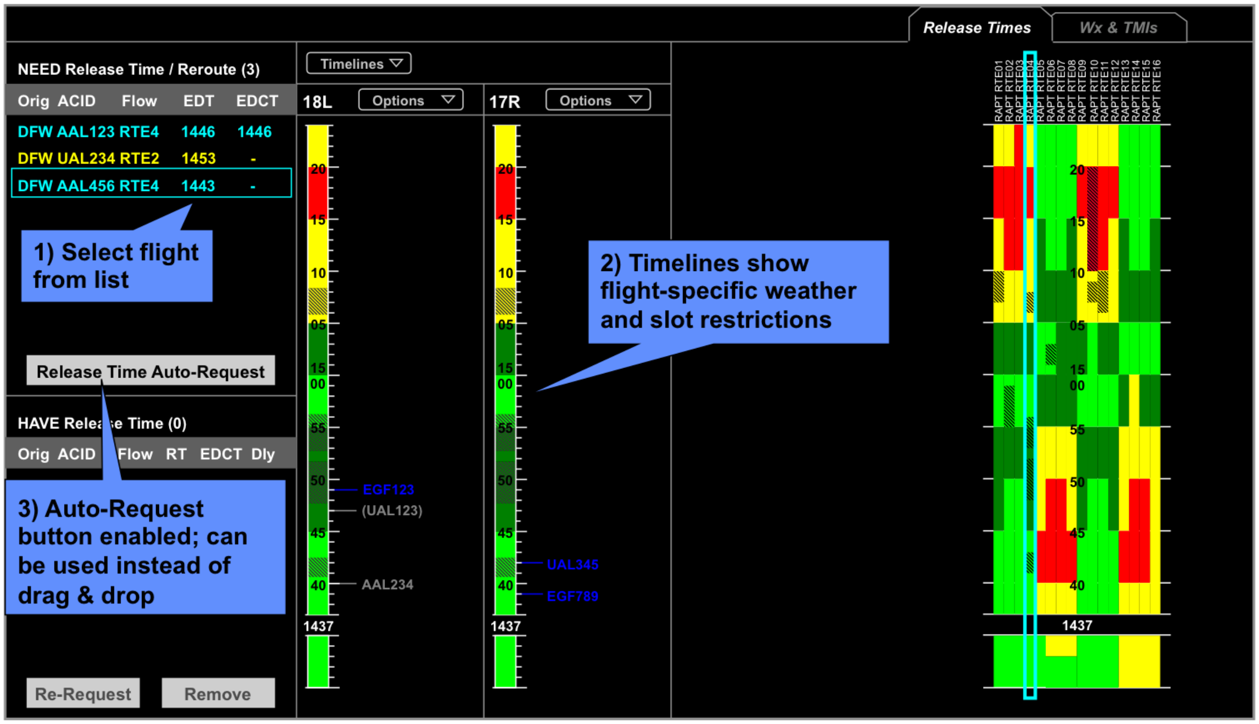

Figure 27: Departure Routing Collaborative Decision Making Display Concept.

category, implementation for field evaluation, were limited by the unavailability of sanctioned operational en route and terminal automation systems to participate in collaborative decision making for departure operations. As a result the capability delivered in the DFW April 2011 version of the TFDM prototype only included integration between TFDM and RAPT. An illustration of the display provided to the traffic management position is given in Figure 28. The field evaluation of the departure routing concept at DFW focused on measuring consistency of information provided by the departure routing module and that provided by other parts of the TFDM system. The evaluation also sought to measure the human factors responses of controller who employs this decision support module. The results found no errors in measurements of consistency of information given by the system to controllers across different interfaces. The human factors responses indicated that the departure routing concept and the information provided by this module was useful for operational efficiency. The test controllers however also indicated that further work was needed to mature the collaborative concept of operations, human-machine interfaces, and the accuracy of forecasted information.

7.4 OPPORTUNITIES FOR IMPROVEMENT

An initial concept for departure routing has been developed and in part implemented for the DFW version of the TFDM prototype. However, there are still a set of steps that need to

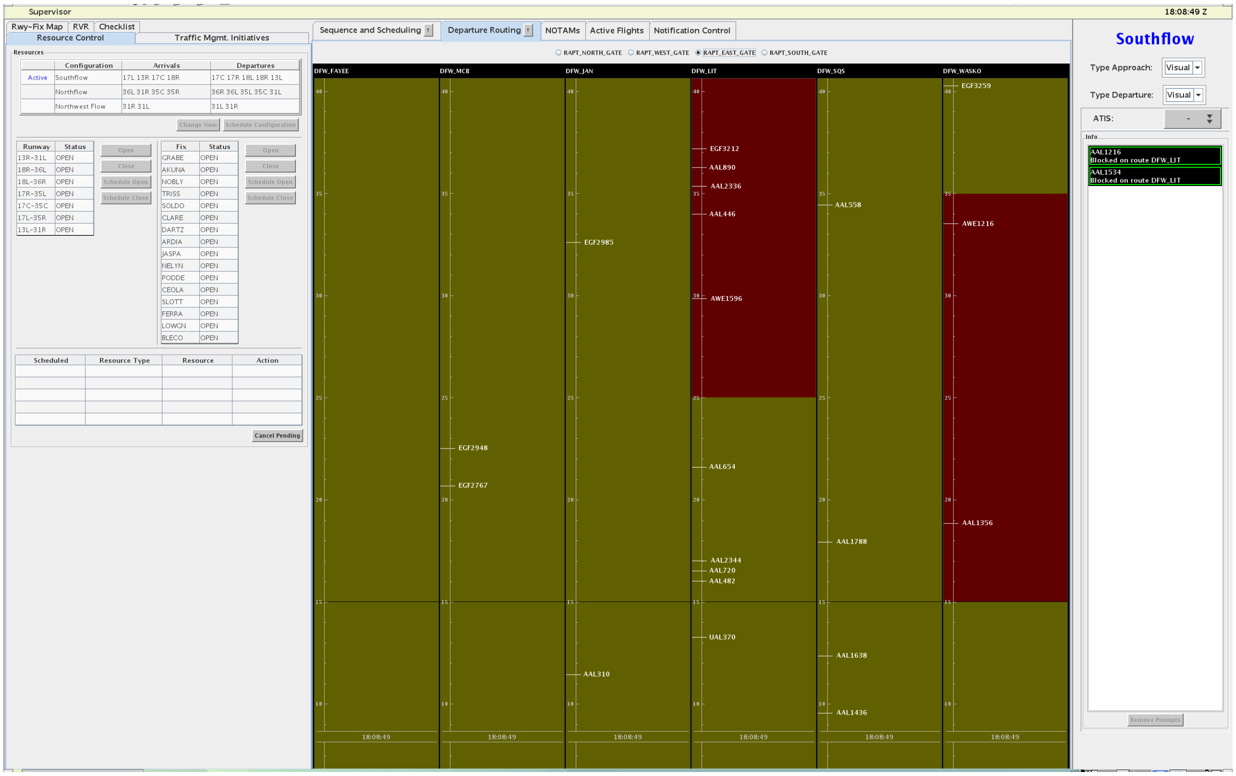

Figure 28: Departure Routing Capability Implemented for DFW.

be taken to mature this implementation to the readiness level needed for operational use for a minimal capability. The FAA's current road-map suggests the development of DR01 as the minimal capability. However, parts of DR03 and DR04 are also needed in order to make DR01 (which is primarily a display capability) operationally useful. An operationally useful minimal capability would then involve TFDM using information from TFMS and TBFM to determine the joint impact of weather and traffic constraints on individual departing flights, and providing indications to the tower controllers. The impact determined by TFDM would then be shared with en route, terminal, and flight operations facilities.

The following is a list of recommended steps for maturing the minimal capability:

- Additional development is needed to update current TFDM prototype. The particular enhancements that need to be made are in: i) Coupling with sequencing and scheduling decision support module to enhance predictions of departure time, and ii) Human and machine interfaces for sharing data with other facilities, iii) Integration with a representation of TBFM
- Human-in-the-loop evaluations to refine user interfaces
- Field evaluations to evaluate operation suitability (including accuracy)
- Adaptation of capability to more than one airport

The delivery of enhanced departure routing capabilities beyond the initial minimal package requires investments to mature both concepts and technologies. A natural extension of the minimal capability discussed above would be the addition of functionality for determining and coordinating re-routes of flights in the tactical time-frame. This enhancement requires foundational work in the: i) definition of a collaborative re-routing concept, ii) specification and validation of external interfaces, iii) algorithms for selecting good route options, iv) predictions on the future status of route options, and v) development and validation of user-interfaces in the tower and collaborating facilities. Some of this foundational work was initiated as part of the TFDM prototype development effort. However significant effort is required for maturing concepts of collaborative departure routing between tower and other facilities. Effort is also required in identifying and raising the readiness level of algorithms for proposing good re-routes under constrained conditions. There are candidate algorithms and approaches that can be leveraged such as some recent work in the area of route identification under convective weather conditions by Pfeil and Balakrishnan [46].

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8. WIND PREDICTION

8.1 OVERVIEW

Historically the actions of wind and weather have played an important role in influencing the decisions of air traffic controllers. However, the desired integration of operationally suitable weather and wind forecasts into a tower decision support system has been slow to evolve. Often the available wind and weather information for terminal and surface operations is either temporally and spatially too coarse, or not sufficiently accurate for effective decision making. For key surface traffic management decisions such as airport configuration change, traffic managers must frequently rely on intuition or experience to guide them. The absence of an integrated terminal wind and weather forecast also make coordination of airport configuration changes challenging. Wind forecasts, for instance, provide valuable information to controllers that can be cognitively integrated for more effective airport configuration management. The direct integration of wind forecasts with automated airport configuration management tools has the potential for even further enhancing controller coordination and decisions.

Accurate and timely short term (0–2 hour) forecasts of surface winds at the airport are important information for airport runway configuration decision support. Unexpected wind shifts can prompt reactive airport reconfigurations that may cause significant delays and increased fuel burn due to increased airborne holding and ground taxiing. For example, Figure 29 shows time series of the surface winds and associated departure delay during a frontal wind shift event that impacted Chicago O'Hare Airport on August 23, 2006. During the time of frontal passage and wind shift at 7:00 pm EDT (00:00 GMT), substantial delays were incurred, with 95 percent of the departing flights delayed more than 15 minutes.

Forecasts of final approach winds are also important for anticipating future airport capacity and estimate airport acceptance rates (AAR). For example, crosswinds may prevent parallel approaches, or overflow runway configurations may be unavailable for certain wind directions.

Some wind shifts, such as those associated with convective weather outflows (e.g., gust fronts), may be short-lived. It is important to know whether a wind shift will be of sufficient duration to warrant an airport reconfiguration. Consequently, wind forecasts need to have sufficient spatial and temporal detail to capture the extents and durations of wind shifts.

Real-time verification and confidence estimates of recent and current wind forecasts are also important quantities that the airport configuration DST should incorporate in order to help users decide whether a suggested airport reconfiguration plan should be implemented.

Existing sources of wind observations and forecasts (described in the following section) were deemed inadequate to meet the update rate, forecast resolution, accuracy, and localization requirements for airport configuration decision support. A prototype real-time surface wind forecast algorithm was therefore developed that provides 5-minute updates of surface wind forecasts for a set of locations out to two hours with 5-minute forecast step resolution. Real-time verification and confidence estimates are also computed.

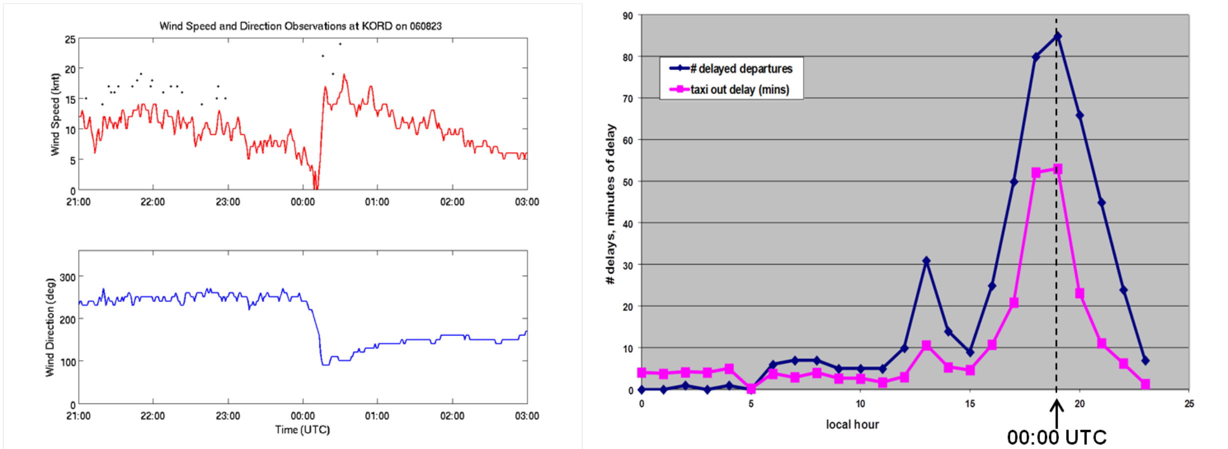

Figure 29: Surface winds and associated departure delay during frontal passage at Chicago O'Hare airport on 08/23/2006. Note wind shift at approximately 00:00 GMT (7:00 pm EDT) coinciding with sharp rise in departure delays.

8.2 STATE OF THE ART

The following summarizes current sources of surface wind observations and forecasts in the airport terminal vicinity.

8.2.1 Sources of Wind Observations and Analyses

- *METARs*

  Meteorological Aerodrome Reports (METARs) are coded weather observation bulletins that are issued hourly at airports and other weather observation stations. Intermediate "special" reports may be issued if there are significant changes in weather conditions. Some METARs are generated by automated weather stations (such as Automated Surface Observing Station (ASOS)). They include current surface wind speed and direction. Forecast winds are not provided.

- *AWOS/ASOS*

  Automated Weather Observation Station (AWOS) and ASOS report surface wind speed, wind direction, and gusts. Real-time ASOS one-minute observations (OMO) are obtainable through FAA's Weather Message Switching Message Center Replacement (WMSCR) service. There are over 4400 ASOS/AWOS stations in the U.S.

- *LLWAS*

  The Low-Level Windshear Alert System (LLWAS) employs a network of wind sensors around the airport to automatically detect and warn of wind shear in the vicinity of the runways. Airports may have as few as 6 or as many as 32 stations. Centerfield winds from the LLWAS network with an update rate of 10 seconds are available through the FAA Integrated Terminal Weather System (ITWS).

- *STMAS*

  The NOAA Space-Time Multiscale Analysis System (STMAS) [47] uses sequential, multiscale variational analysis techniques to assimilate and analyze high-frequency weather observations and generate 3D CONUS-domain gridded analyses of atmospheric variables at 5-km grid resolution every 15 minutes.

- *ITWS Terminal Winds*

  The ITWS Terminal Winds (TWINDS) product combines data from the 13-km NOAA Rapid Refresh numerical model with observations from ground stations (e.g., ASOS, AWOS, LLWAS), aircraft reports, and Doppler weather radars (Terminal Doppler Weather Radar (TDWR), Next Generation Radar (NEXRAD)) to provide 5-minute updated estimates of horizontal winds in the terminal area. The operational system does not output the internally computed 3D wind grids (2-km resolution out to 120 km, and 4-km resolution out to 240 km), but only outputs a limited number of vertical profiles through the 3D grids at user-specified locations (often corresponding to navigational fixes). It is diagnostic only (no forecast capability), which limits its usefulness for airport configuration planning.

8.2.2 Sources of Wind Forecasts

- *Terminal Aerodrome Forecasts (TAF)*

  The Terminal Aerodrome Forecast (TAF) is the most commonly used source of forecast wind information for aviation in the airport terminal area. TAFs provide forecasts of weather conditions in a coded text format (similar to METAR) within five miles of the airport over the next 24–30 hours. They are typically updated every 6 hours, but special intermediate updates may be issued if changing weather conditions warrant. TAFs are generated based on local forecaster knowledge with guidance from numerical model forecasts, and include expected surface winds.

- *NWP models*

  Numerical Weather Prediction (NWP) models continue to advance with regard to increasing numbers and types of observations, data assimilation techniques, improved physics, and increased computational power resulting in increasingly accurate, higher resolution, frequently updated forecasts for a wide range of important meteorological variables.

  - *RAP*

    The hourly updating 13-km resolution Rapid Refresh (RAP) model has recently replaced the Rapid Update Cycle (RUC) as the operational gridded forecast model produced at National Oceanic and Atmospheric Administration National Centers for Environmental Prediction (NOAA/NCEP). Gridded forecasts of winds and gusts are produced for the North American domain for hourly forecast time steps from 0 to 15 hours at selected altitudes and at regular pressure altitude levels (50 vertical levels every 25 hPa to 10 hPa).

· *HRRR*

The High Resolution Rapid Refresh (HRRR) model is an experimental hourly updating, 3-km resolution, CONUS domain model that is initialized and run by National Oceanic and Atmospheric Administration Earth System Research Laboratory (NOAA/ESRL) as a nest within the Rapid Refresh model. Although it is experimental, it is mature and widely used by a variety of aviation agencies and weather information producers. It is targeted for operational deployment around 2014. Like the RAP, HRRR updates hourly, providing hourly forecast grid sequences of meteorological variables from 0 to 15 hours. It provides the same wind products as the RAP model.

· *LAPS*

NOAA's Local Analysis and Prediction System (LAPS) [48] is a widely used research data assimilation system and forecast model that incorporates a wide variety of global, national, and local data sets into analyzed grids. Data sources are typically assimilated hourly and include local networks of surface observations, Doppler radars, satellites, wind and temperature profilers, and aircraft. Numerical models such as Weather Research and Forecasting (WRF) (the underpinning for RAP and HRRR) can be initialized with LAPS analyses to provide short-term forecasts. Horizontal, vertical, and temporal resolutions are adjustable. A recently developed configuration called Variational LAPS (V-LAPS) employs multi-scale successive correction (starting with large-scale NWP models as backgrounds for analysis and prediction, and variational analysis techniques.

- *WTMD Wind Forecast Algorithm (WFA)*

  The Wake Turbulence Mitigation for Departures (WTMD) algorithm was developed at MIT Lincoln Laboratory and is presently undergoing prototype testing by FAA at selected airports. It incorporates a Wind Forecast Algorithm (WFA) that has a surface wind forecast component that applies a statistical approach using recent observations of winds from 1-minute ASOS observations. A training set of prior ASOS observations are used to generate the statistical predictors. Surface wind now-casts are generated for a single point every minute and are considered valid for the following 20 minutes. The wind forecasts from WTMD are not currently operationally available. However the statistical prediction techniques may prove useful for future enhancements to the current prototype surface wind forecast algorithm.

Although each of the above wind information sources are generally useful, they are deficient in one or more capabilities that are needed in order to better plan for airport configuration changes. They either don't have a forecast capability, aren't locationally specific enough, don't update frequently enough, or don't have the desired forecast temporal resolution. In addition, useful forecast quality metrics such as real-time accuracy scores for prior forecasts and forecast confidence estimates for current forecasts at the specific locations of interest aren't available from these data sources.

8.3 TFDM PROTOTYPE CAPABILITY

To address the deficiencies of existing wind forecast products for runway configuration decision support, a prototype real-time automated surface wind forecast algorithm was developed that currently operates as a shadow process on the Lincoln Laboratory CoSPA system. This algorithm was not, however, integrated into the TFDM prototype demonstrated at DFW. The wind forecast capability provides 5-minute updated predictions of surface winds at 5-minute forecast intervals out to two hours for a configurable set of wind forecast locations. Real-time wind forecast accuracy scores and confidence estimates are also provided through automated comparison of wind forecasts with corresponding one-minute surface observations (e.g., ASOS).

The surface wind forecast algorithm was implemented as a module within the Automated Front Detection (AFD) algorithm previously developed under FAA's Aviation Weather Research Program. Figure 30 is a high-level process and data flow block diagram of the automated front detection algorithm with the surface wind forecast enhancements, collectively referred to as "FrontsWindsProc". The NOAA fronts input shown in the diagram is used for the automated front detection processing, but is not currently part of the wind forecast product generation.

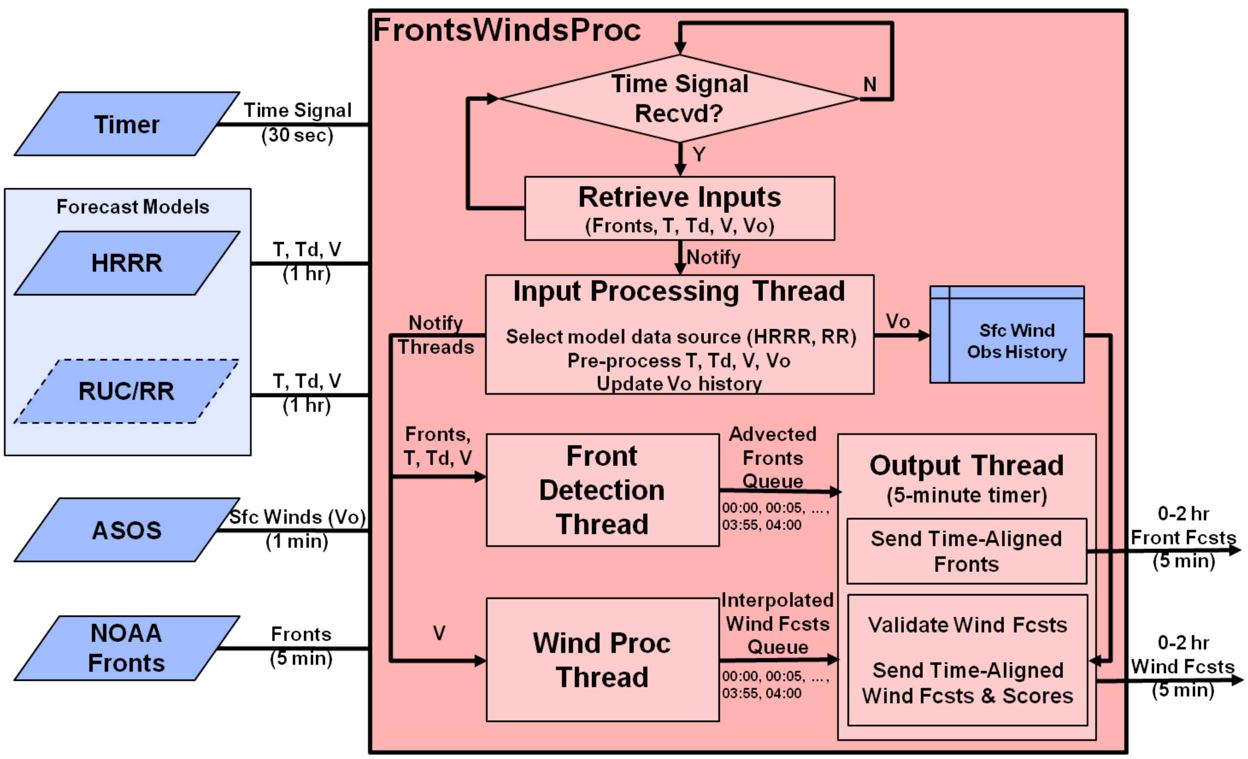

Figure 30: Block diagram showing process and data flow for the automated front detection and wind forecast algorithm.

8.3.1 Inputs

The primary data source for the surface wind forecast algorithm is a forecast time sequence of gridded numerical model surface winds. The experimental HRRR model is an hourly updated, CONUS domain 3-km resolution model produced by the NOAA/ESRL, and is the preferred input for the wind forecast because of its high spatial resolution and accuracy. Alternatively, the algorithm can be configured to process gridded forecast winds from other operational NWP models such as Rapid Refresh (RAP).

Each hourly generated HRRR model data set contains forecast grids for hourly forecast intervals from 0–15 hours of meteorological variables. For the surface wind forecast, the 10 meter wind (U and V-components) and gust products from the HRRR are the specific wind products used. Figure 31 is a plot showing a 1-hour forecast of the 10 meter winds from the HRRR.

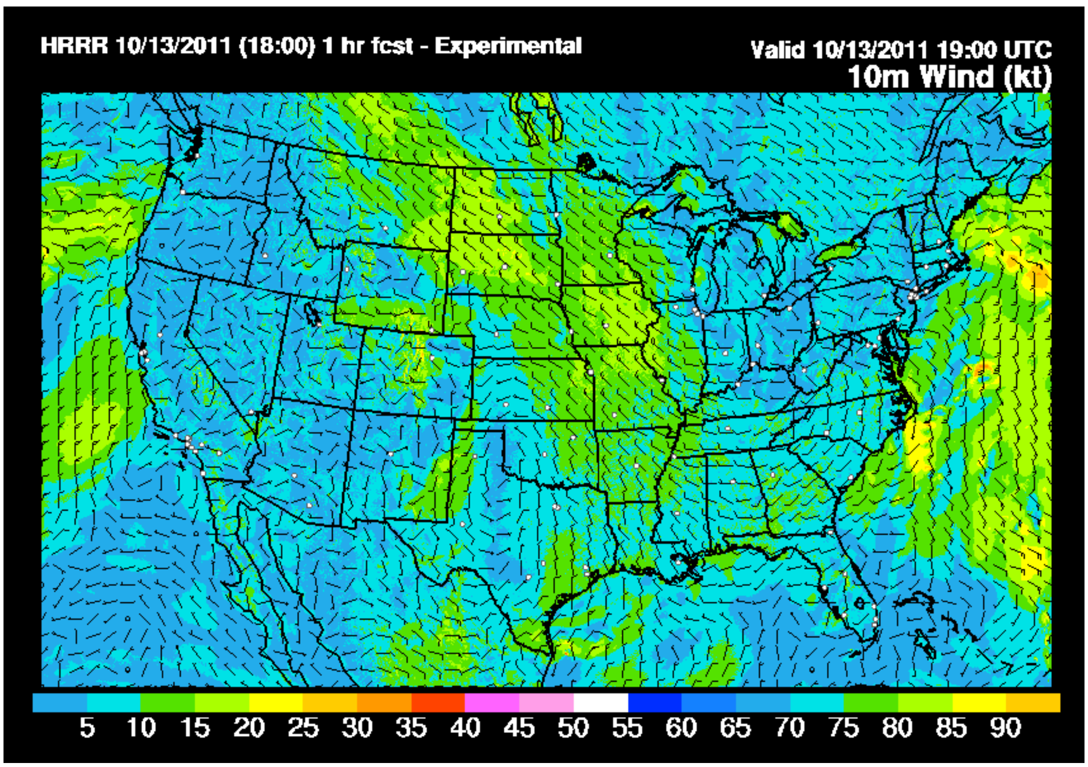

Figure 31: Example display of HRRRR 1-hour forecast winds.

There is considerable latency between the model initialization time and the completion of the model run and its subsequent transmission and receipt. The total latency is typically between 90 and 105 minutes. The implication of this is that a 1-hour surface wind forecast issued at a given update time will be based on a time-interpolated value between the 2- and 3-hour forecasts of the prior model run.

Real-time one-minute observations of surface winds from ASOS are also ingested and used for continuous real-time verification (accuracy) of prior wind forecasts and for confidence estimation of the current wind forecasts. If ASOS data for a wind forecast site are unavailable, then the wind forecast algorithm uses the current gridded forecast model wind observation data (model initialization field) to verify the prior forecasts.

8.3.2 Processing

A 5-minute interval timer signal is used to trigger processing. When the timer signal is received, the algorithm checks the model forecast wind data input buffer and the OMO ASOS data buffer. It then retrieves and stores the accumulated data. If the needed set of forecast wind grids have been received, the wind forecast generation process begins (to account for latency, forecast grids out to four hours are needed in order to generate the 0–2 hour forecasts).

The algorithm iterates over each of the configured wind forecast site locations, obtaining the wind value at the corresponding model grid location from each hourly interval model forecast out to 4 hours. The intermediate result is a 0–4 hour forecast wind time series with 1-hour resolution for each location. In order to support the desired 5-minute wind forecast updates with 5-minute forecast resolution, the 1-hour resolution forecast wind time series are temporally interpolated using linear time interpolation between retrieved model forecast wind values at times preceding and following the intermediate forecast time. Wind magnitudes are interpolated separately from directions to preserve magnitudes when wind directions are changing rapidly over the interval being interpolated.

Once the interpolated forecast time series have been computed for each site, they are stored in a fixed time length output queue. Old forecast data are aged off of the back of the time-ordered queue as new forecasts are added. Every five minutes, a separate output processing thread accesses the forecast time series from the queue and issues the time-matched subsets of forecast data valid for 0–2 hours from the current time.

8.3.3 Output

Two types of output products are generated every five minutes. The first output product is a time series of current 0–2 hour wind forecasts and prior wind forecast accuracy for forecasts issued over the preceding hour. This product information would be used by the TFDM airport configuration capability, and could additionally be presented in tabular form as shown on the right in Figure 32. The tables include accuracy (for prior forecast history) and confidence (for the current forecasts). Confidence scores are computed based on the root mean square (RMS) forecast errors of recent prior forecasts compared with the most recently obtained wind observations (from ASOS if available, or from the latest HRRR initialization if ASOS is not available).

The second is a wind vector time series product that includes historical (observed) and current forecast wind vectors for the set of forecast sites over a -2 to $+2$ hour time interval with 5-minute resolution. A graphical display such as that shown in the left of Figure 32 could loop these to visually show the prior and future spatio-temporal trends of the winds in the region.

Figure 32 shows notional display concepts that could be utilized on a “weather tab” on the TFDM display or on a Consolidated Storm Prediction for Aviation (CoSPA) type display at airports where TFDM is not available.

To provide products to the TFDM airport configuration DST and to support other potential NextGen consumers, the output products are converted to XML format utilizing Geography Markup Language (GML), and following Open Geospatial Consortium (OGC) standards such as Observations and Measurements (OM), and Weather Exchange Model (WXXM).

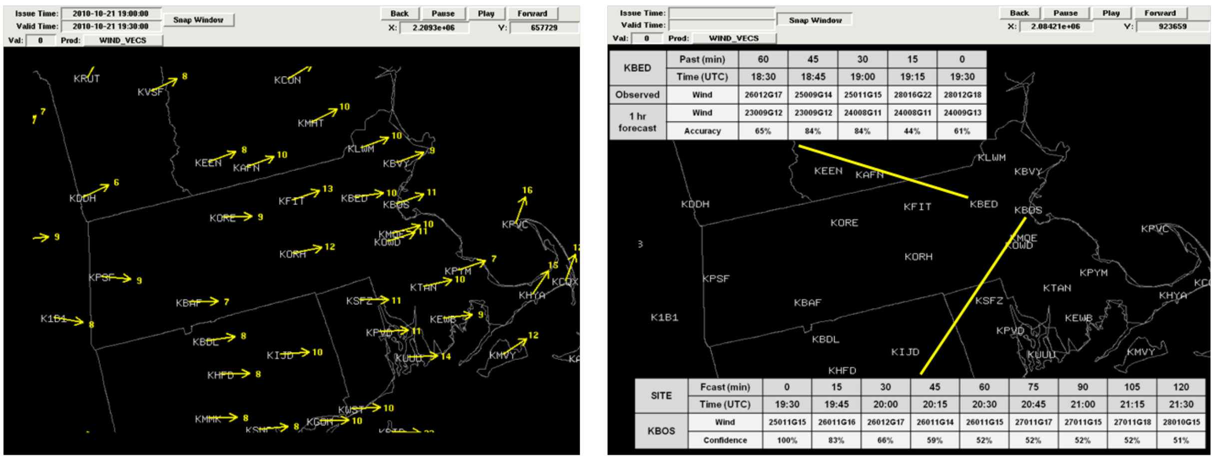

Figure 32: Notional wind forecast display concepts.

8.3.4 Performance

Figure 33 shows a comparison of 1-hour surface wind forecasts against corresponding ASOS observations at EWR for a 9-hour period on 12/12/2010 during which a frontal wind shift occurred, prompting a ground delay program (GDP). The results show that the underlying HRRR model forecasts were quite accurate with regard to wind speed, but forecast wind directions were somewhat out of phase temporally during the wind shift, with occasional direction errors as large as 30 degrees. Dynamic wind events such as this frontal wind shift represent one of the more challenging forecast scenarios.

A rigorous performance assessment has not been conducted for the surface wind forecast algorithm. Aggregate performance statistics could be culled from archived real-time accuracy statistics (assuming ASOS data are available for truth comparison). Forecast accuracy for the prototype surface wind forecast algorithm should be comparable to that of the underlying NWP model (e.g., HRRR), since the initial algorithm primarily interpolates between the model forecast grid points in space and time. Aggregated RMS forecast errors for the HRRR 10-meter wind forecasts out to six hours lead time are reported to be 3.5 m/s or less [49]. However, aggregate RMS error statistics may not capture occasional larger errors that may occur during more dynamic wind events, such

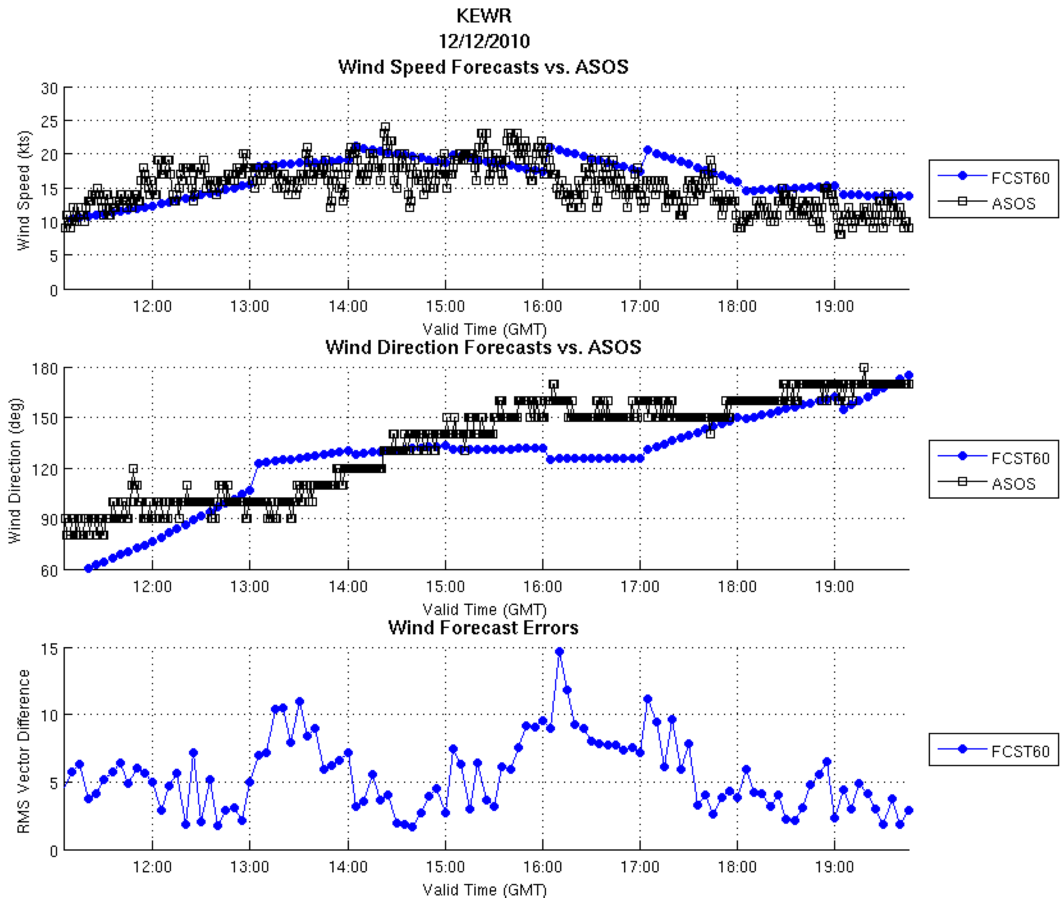

Figure 33: Comparison of 1-hour surface wind forecasts (blue curve) against ASOS observations (black curve) at KEWR during 11:00–20:00 GMT on 12/12/2010. Corresponding RMS forecast errors are shown in the lower plot.

frontal wind shifts.

8.4 OPPORTUNITIES FOR IMPROVEMENT

An initial prototype real-time rapid update surface wind forecast algorithm has been developed that currently operates on the Lincoln Laboratory CoSPA shadow research system. The algorithm generates 5-minute update point forecasts of surface winds through spatial and temporal interpolation of time-adjusted HRRR model forecast winds. Prior forecasts are continuously validated against surface observations to generate accuracy scores, and confidence values are assigned to each forecast going forward.

There are several areas for maturing and extending the initial wind forecast capabilities.

Figure 34 shows one possible 3D terminal winds forecast architecture that incorporates suggested improvements described in the following sections.

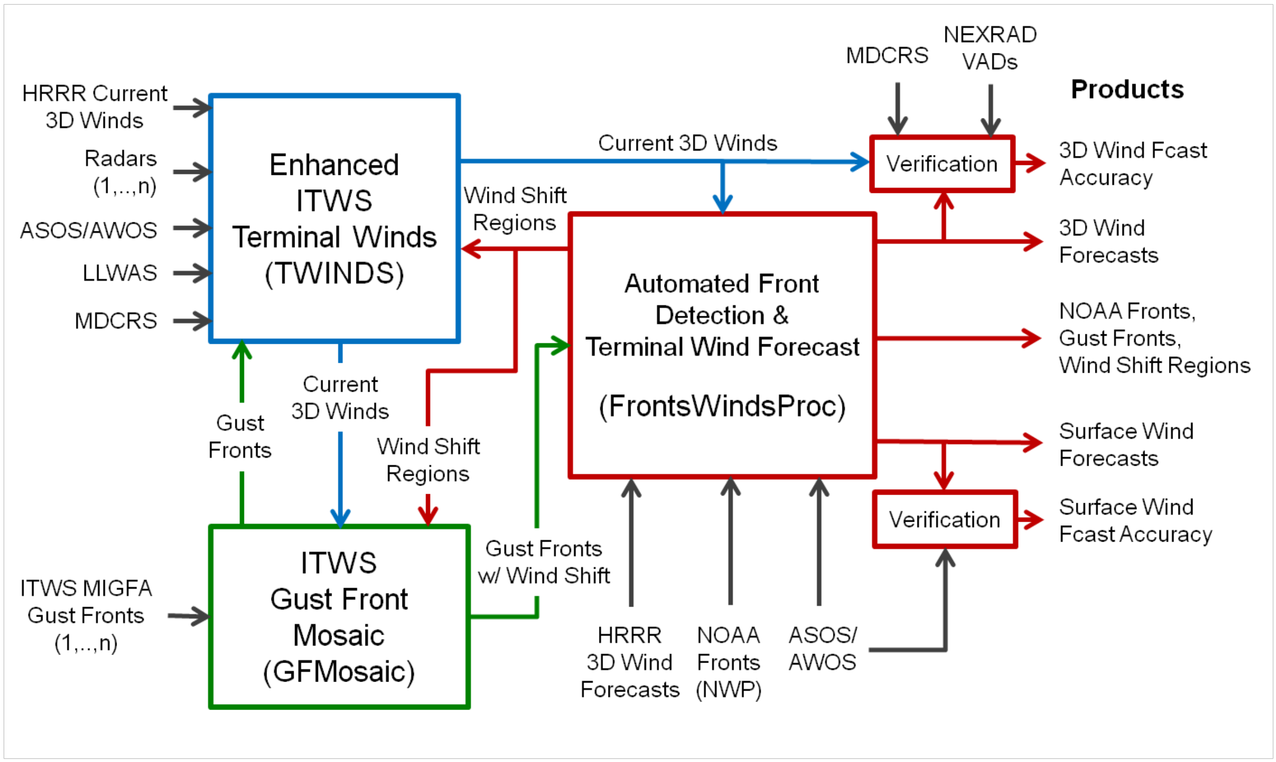

Figure 34: Example 3D Terminal Winds Forecast Architecture.

8.4.1 Forecasting of 3D Winds Aloft

Although surface wind forecasts are the primary wind information requirement for runway configuration planning, forecasts and characterizations of winds aloft are also important. Airport acceptance rates (AAR) and TBFM scheduling may be adversely impacted during periods with strong winds aloft or vertical wind shear where merging and descending traffic may have sharply different ground speeds due to changing headwinds. When choices exist between multiple candidate runway configurations, arrival throughput and controller workload considerations in the presence of adverse winds aloft may influence the choice of an optimum runway configuration.

3D wind forecasts from current operational and experimental numerical models such as RAP and HRRR do not take advantage of high resolution, rapid update analyses from systems such as ITWS TWINDS or NOAA LAPS. Furthermore, short lead-time numerical forecasts (e.g. 0–3 hours) can have poorer accuracy than longer lead time forecasts due to issues related to numerical model “spin-up”. Following a approach successfully utilized by CoSPA and NWP for precipitation forecasts, short-term trends and extrapolations of ITWS TWINDS analyses or short-term forecasts from other high-resolution analysis and forecast models such as LAPS can be blended with HRRR forecasts to improve forecast quality for short lead times.

Additionally, the use of numerical model forecast time ensembles (collections of different lead-time forecasts from prior model runs all having the same valid time) to generate consensus forecasts should be investigated. Optimum ensemble combining weights that minimize headwind or time-of-flight prediction errors, for example, can be determined using random regression forest techniques similar to those utilized by the CoSPA Airspace Flow Program (AFP) blockage-based capacity forecast [50].

8.4.2 Forecast Verification and Confidence

Real time verification (accuracy scores) and confidence estimates for wind forecasts are critical accompanying information needed to support traffic management decisions. The prototype surface wind forecast algorithm described previously computes accuracy scores for prior forecasts by comparing them against corresponding surface wind observations such as ASOS and AWOS. Accuracy scoring is currently based on a linear scaling of the RMS vector errors between the forecast and observed winds. This error metric will likely need to be adjusted based on user experience and feedback to ensure that it provides meaningful representations of the prior forecast performance. Confidence estimates for the prototype surface wind forecasts are currently based solely on extrapolating prior forecast accuracy, but additional factors such as spatial or temporal variability of the winds near the particular location could be factored into the confidence values.

Verification scores and confidence estimates are also important accompanying components for winds aloft forecasts. Depending on availability and suitability, observations from aircraft or nearby Doppler radars (e.g., NEXRAD or TDWR wind profile VADs) can be used as truth observations for verification of forecast winds aloft. Gridded wind analyses from ITWS TWINDS could also be used since those analyses incorporate these radar observations.

8.4.3 Locations and Movements of Fronts

For tactical and strategic planning, it is important that traffic managers have the ability to see current as well as forecast winds at surrounding locations, especially at sites "upstream" of approaching frontal boundaries. Air traffic planners, therefore, need to be able to see current and forecast front positions in order to know which post-frontal and pre-frontal locations are germane for monitoring winds and wind forecast performance. The NextGen Weather Processor (NWP) is slated to provide motion-compensated 5-minute updates of current and forecast synoptic fronts derived from National Oceanic and Atmospheric Administration Hydrometeorological Prediction Center (NOAA/HPC) surface weather analyses, while ITWS currently provides current and forecast locations of gust fronts. Additional indications of frontal wind shift regions could be provided by algorithms such as the experimental AFD algorithm described earlier. These front locations and forecasts should be displayed to users along with the wind forecast and accuracy information at surrounding sites (see Figure 35).

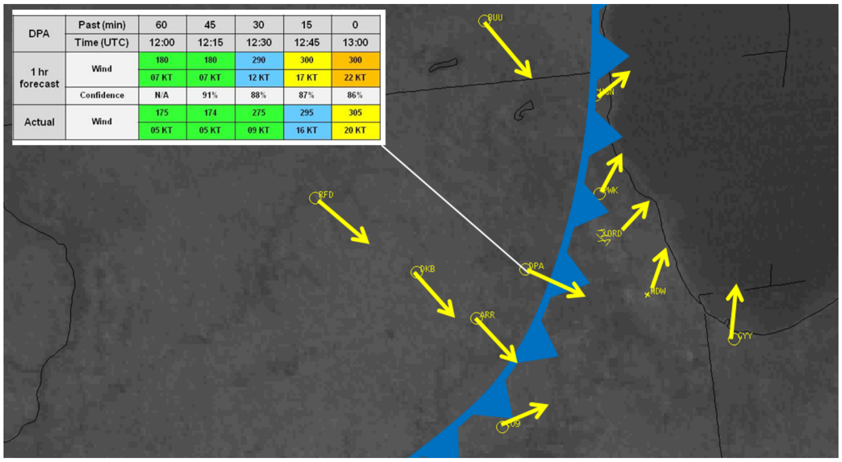

Figure 35: Example user display showing a cold front and current winds with forecast verification for a selected "post-frontal" location

8.4.4 Improved Surface Wind Shift Forecasts

Planning for wind shifts arising from mesoscale boundaries such as gust fronts and sea breezes is an important element of surface management in many locations in U.S., especially in the summer months. The ITWS gust front algorithm (Machine Intelligent Gust Front Algorithm, or MIGFA) detects and warns of potentially hazardous wind shifts from thunderstorm gust fronts, but it was not designed to detect weaker wind shifts such as sea breeze fronts. Its usefulness for airport configuration planning is limited because it only provides a single wind shift estimate indicating the winds behind the gust front at a single location and time-distance (10 minutes) behind the front. Furthermore, there is no indication of the duration or trend of the expected wind shift, which is important for deciding whether it will be worthwhile to change runway configurations. The accuracy of the ITWS gust front wind shift forecasts also varies considerably due to its reliance on single-Doppler radar wind analyses.

At ITWS locations with multiple, overlapping TDWR coverage, the ITWS Gust Front TRACON Map (GFTMAP) algorithm uses a static, site-specific rule set to prioritize which radar's gust front detections will be used at each location within the TRACON. The static rule set often fails to choose the radar having the most fully detected gust front (or may even choose a radar that failed to detect it at all). As part of a planned ITWS upgrade, the GFTMAP algorithm would be replaced by the Gust Front Mosaic (GFMosaic) algorithm. GFMosaic effectively blends (as opposed to selects) gust front detections in regions of overlapping coverage, and has an additional capability to ingest externally computed gridded surface wind analyses (e.g. ITWS TWINDS grids) to further refine the gust front wind shift estimates. Synergistically, the TWINDS algorithm would benefit from knowing the locations of gust fronts and other wind shift boundaries in order to avoid smoothing the winds across the frontal boundaries and therefore better preserve the strength of the wind shift across the front.

Finally, externally generated non-gust front wind shift regions (e.g. synoptic or sea breeze front regions from the Automated Front Detection algorithm) could also be ingested by GFMosaic and used to further support the fusion of wind shift boundaries in the mosaic. This capability is currently under investigation by Lincoln Laboratory.

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9. RECOMMENDATIONS

This section summarizes the recommendations for follow-on activities based on the status and maturity of decision support tools as reported in the previous sections. The recommendations are grouped along the three high benefits potential areas discussed at the beginning of this report.

Management of runway queues and sequences: The complexity of surface operations, as well as uncertainties in traffic and weather constraints are a challenge to predicting queue occupancy and runway sequences. The listed maturation steps can assist with mitigating these challenges:

- Mature foundational algorithms for flight movement modeling and prediction for surface and terminal region.
- Mature queue size prediction, metering, and runway sequencing algorithms to achieve higher accuracy and robustness while encountering uncertainties in traffic constraints, weather constraints, operator/controller decision processes, and reliability of surveillance/flight data. Improving decision support for management of convective weather constraints is particularly important given the high degree of surface management inefficiency (e.g., long taxi out delays) during convective weather.
- Adapt algorithms to a set of diverse airport and metroplex sites, and derive adaptation requirements.
- Perform a more rigorous analysis of benefits based on data collection (in part using simulation) for a diverse set of airports.

> Progress on these steps can be initiated by leveraging algorithms and concepts developed during earlier prototyping efforts. These algorithms (such as improved taxi-time and queue occupancy prediction models) can be integrated into ongoing prototypes and matured through field or simulation testing for a diverse set of airports. These efforts can also leverage the past and ongoing efforts by N-control in maturing departure metering concepts.

Tactical management of flight routes and times: Inefficiencies in this area typically arise from uncertainties in weather, airspace traffic demand, traffic initiatives, and complexity in coordination of flight route and times with other facilities. The recommended follow-on activities for maturing concepts in this area are:

- Mature concept for collaborative departure route and time management between surface automation, TBFM, TFMS, and airline flight operations.
- Develop surface automation algorithms and procedures for selection of feasible flight routes and times.

- Develop algorithms that forecast the impact of constraints (weather and traffic) on pending departure flights. A surface capability is important here because the richness of information related to impact on flights and context surrounding the impact is readily available to tower automation (as illustrated by the TFDM prototype). Furthermore, the tower is a key contributor to decision making in managing airport configuration.

- Develop interfaces for sharing predictions from surface decision automation systems with collaborating facilities.

> Interface (exchanges with time based metering, traffic flow management, and airlines) and algorithm development initiated during previous surface prototyping efforts can be leveraged to quickly establish a capability for the demonstration and maturation of multi-facility (or multi-automation system) coordination in the management of departure flight routes and time slots under tactical operations. Experience that has been gained throughout the demonstration of IDRP can also assist concept maturation in this area.

Managing airport configuration changes: The dominant factor in managing airport configuration change is the ability to accurately forecast terminal area winds. Common access to these forecasts and the corresponding predicted state of surface operations amongst coordinating facilities is important for effective decision making. Therefore the following maturation steps are deemed necessary.

- Mature concept for automation assisted multi-facility coordination of airport configuration management.

- Mature algorithms for accurate terminal area wind prediction, and algorithms for assessing the impact of terminal winds on predicted airport throughput for feasible configurations.

- Adapt and extend algorithms to account for impact on throughput for interdependent metroplex environments.

> In this area follow-on maturation activities can begin by leveraging wind prediction algorithms developed during prior prototyping efforts. Although these algorithms have yet to be integrated into a surface automation prototype, a foundational capability for affecting airport configuration change exists and has been demonstrated by the TFDM prototype system. This foundational capability can also be extended to provide an initial means for inter-facility coordination of airport configuration.

The recommendations for each of the benefits areas are supplemented with general recommendations on activities designed to mature the decision support capabilities to the level suitable for operational use. The specific recommendations are:

- Establish a technically informed roadmap for incremental development of key decision support functions.
- Perform rigorous benefits studies using a mix of fast-time simulations, human-in-the-loop experiments, and field experiments.
- Conduct prototyping activities designed to validate the readiness of decision support algorithms and concepts of use.

Figure 36 suggests an approach for the evolutionary delivery of individual capabilities which make up each DST area, together with MIT/LL's estimates of current relative maturity level and potential benefits. We note that the TFDM prototyping effort has made significant strides in maturing many concepts related to decision support functions for airport surface operations. However, these strides need to be supplemented with additional improvements in concepts, designs, algorithms, and validation (through simulation or testing) in order to deliver the high benefits potential from the more advanced TFDM algorithms.

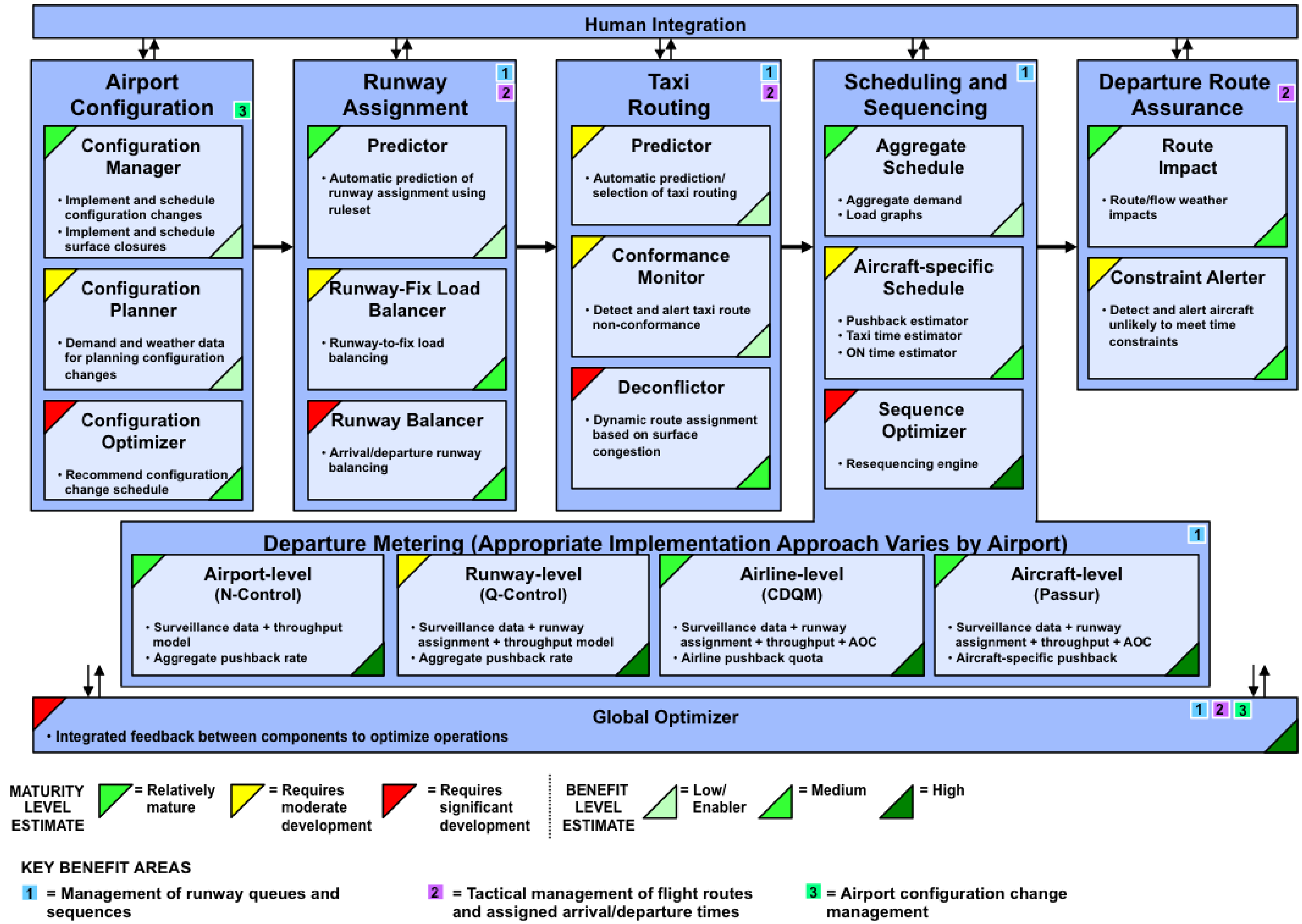

Figure 36: DST capability evolution with maturity and benefits estimates.

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