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A Framework for Modeling Air Traffic Control Systems

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ABSTRACT

The strategic planning and tactical execution of Air Traffic Control (ATC) provided by Air Navigation Service Providers (ANSP) are often not aligned and lead to inefficiencies in the Air Traffic Management (ATM) system. This paper proposes an analytical framework for the air traffic control system based on a system-of-systems paradigm, with a hierarchy of nested and cascaded feedback control loops—one or more for each type of control service. The framework is then used to assess the stability and response to random variables, such as poor weather and equipment failures. The performance of each control loop is then described qualitatively and validates the framework for investigating the benefit of new policies and technologies.

INTRODUCTION

Except for a brief period after the September 2001 tragedy, air traffic in the US has grown significantly leading to increased congestion and delays. According to the Joint Economic Committee Report, flight delays and congestion cost US airlines $41 billion in 2007 [1]. Another report estimates that flight congestion and delays at New York City's three airports cost the regional economy $2.8 billion in 2008 [2].

Airlines are cutting routes to deal with the economic recession. The outcome is packed airplanes with load factors near 85% for the top nine US airlines in July 2009. Despite the cuts in capacity, the on-time performance has improved to only 78.9% for 2009 [3]. The ICAO, however, predicts this phenomenon will change as the economy improves. Modest growth of ~2.6% is forecast for the US in the next 2 years [4]. Indeed, the National Airspace System (NAS) is unable to meet today's demand, and will likely fail with the projected increase in traffic. Weather events compound the problem, and new airports and runways will not improve the situation without improvements to the current capacity limitations.

Delays increase fuel burn, cycle times, and crew times, which increase the airlines' O&M costs significantly. A congressional report estimates the airlines spent $19.1 billion in additional fuel, crew and maintenance costs due to delays in 2007 [1]. ICAO projects that the world scheduled air carriers will lose $8.9 billion in 2009 [4]. These loses threaten the airlines' survival. Moreover, the impact on the environment is dramatic. For every unit of fuel burnt, approximately 3.16 units of carbon are released into the atmosphere.

CAUSES OF DELAYS - There are three main reasons for air traffic delays: infrastructure, weather and traffic. Among the three, equipment and weather are the most frequent.

Infrastructure - The current NAS infrastructure was built in the 1950s and is aging. We still use 1960's communication technology, and the equipment has not kept pace with technology. The Global Positioning System (GPS) has not been fully applied to aviation, even though it is ubiquitous in cell phones and car navigation [5]. The current NAS is still dependent on ground-based navigation aids, and because of coverage limitations, airspace users are forced to stay within the range of surveillance radar and follow a "single highway" This results in congested highways and gives rise to intractable routing conflicts.

Weather -A NextGen Joint Planning and Development Office (JPDO) report estimates that 70% of the NAS delays are caused by weather in the continental US [6]. This is due to obsolete equipment, inferior weather prediction tools and inconsistent use of weather information in decision making.

DEALING WITH THE SITUATION - Air Traffic Control (ATC) is a service provided by ground-based controllers who direct the flow of airplanes on the ground and in the air [7]. Whenever conflicts arise due to weather or the limited means of managing large traffic volumes, controllers ensure safe aircraft separation by delaying the aircraft on the ground or introducing additional space between aircraft to slow the traffic flow. Additional tools include holding aircraft in a particular sector or rerouting to less congested airspace. All of these actions are necessary because of the equipment and weather prediction tools are inadequate for the methods of traffic control and the volume of traffic.

Both the United States and Europe have realized the need to address these inefficiencies, and have launched NextGen and Single European Sky ATM Research (SESAR) initiatives.

NextGen – The US has launched NextGen initiatives to enhance safety, increase efficiency and capacity, and reduce the environmental footprint. It is a curb-to-curb process that includes the activities inside the airport (security, baggage handling, et cetera) as well as with aircraft. If not repaired, the FAA estimates the broken air transportation system will cost US taxpayers $22 billion by 2022, and will likely grow to $40 billion by the 2030 [8].

SESAR – Similarly, Europe has launched SESAR with ambitious goals of a threefold increase in system capacity by 2020, improvement in safety by a factor of 10, a 10-percent reduction in environmental impact per flight, and a 50-percent reduction in ATM costs. SESAR is a gate-to-gate effort that accounts for the difficulties of multiple airport ownership in multiple countries. SESAR will cost an estimated €30 billion, including deployment [9].

An Air Traffic Control system is a complex system to model. Yet, a theoretical model must be developed to study the current performance and identify and validate future improvements in policy and computer automation technology.

SCOPE OF THIS PAPER – The current work was initially motivated by the need to identify the cause of the inefficiencies in the existing ATC system. From this work it became evident that the following questions must be answered to achieve the increased capacity, safety enhancements, and reduced environmental footprint promised by NextGen and SESAR.

1. Is there a framework that abstracts the function of the current Air Traffic Control System?
2. Can the effects of improvements proposed by NextGen and SESAR be analyzed in this framework in the presence of external stimuli?

The external stimuli that affect the system include:

- Adverse Weather (Wx)
- Infrastructure limitations and equipment failures
- Pseudo-random traffic volume

This paper introduces a framework for evaluating and assessing the current ATC system and future improvements. The proposed model is based on a system-of-systems paradigm, with a hierarchy of cascaded feedback loops—one or more for each control service. The model is developed by first identifying the basic control loops for each level and type of service.

The scope of the paper is limited to describing the abstract model and then mapping the current air traffic control system to this representation. The framework is then used to assess the stability and response to random variables, such as weather and equipment failure. The model is then used to analyze NextGen improvements, such as 4D-Weather cubes and ADS-B, to identify the benefits of weather and equipment improvements. The analysis is restricted to commercial airline operations.

This paper differs from prior work by functionally partitioning the current ATC system into strategic planning, tactical planning, and tactical execution. The impact of Information Technology and some pilot-oriented tactical functions are described in [10]. The future NAS operational concept is described at a higher level with feedback loops in [11]. Traffic Flow Management is modeled using mathematical models that are useful for simulation purposes in [12]. Modeling of cognitive tasks of the controllers is described in [13]. The merits of centralized versus distributed ATC systems is discussed in [14].

THE ABSTRACT MODEL

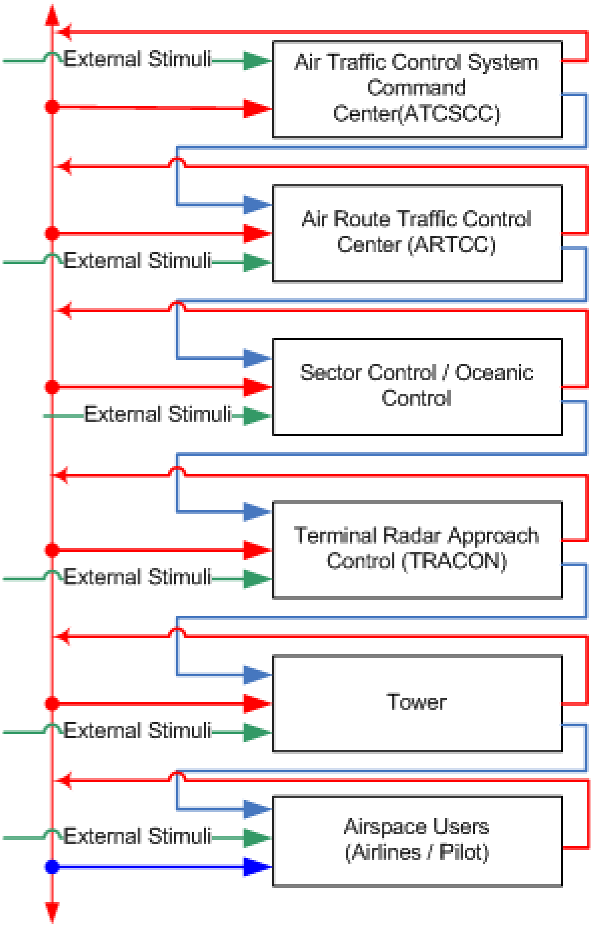

Fig. 1. Abstract model of ATC flow

The ATC system can be visualized as a hierarchical system, with the Air Traffic Control System Command Center (ATCSCC) being at the top and the Air Route Traffic Control Center (ARTCC), Sector Control, Oceanic Control, Terminal Radar Approach Control (TRACON) and Tower control at the lower levels. Since changes to the existing ATC structure are not considered in the NextGen documents, the abstract model assumes the ATC structure will remain the same.

In the abstract model, as shown in figure 1, all of the processed inputs from a higher level are shown in blue. This is to show the hierarchical nature of the information flow. In this abstract model, the functionality of the TRACON is assumed to be a subset of the Sector Control and hence lower in the hierarchy. The functions of each of the components are described in the next section.

The model depicts the feedback that occurs at various levels whenever a significant event happens that can threaten the stability of the system. Real life examples include a weather system that is localized to a particular hierarchical level and can result in conflicts. The feedback loop shown in red terminates at a common communication channel that facilitates information exchange. This communication channel is shown in red on the left side of the diagram as a bi-directional arrow.

The communication channel is bi-directional as there is a need to skip levels when a significant event happens. Another reason is to accommodate the net-centric solutions that are proposed for both NextGen and SESAR.

The green arrows represent external stimulus such as weather events, ground equipment breakage, or traffic congestion that can alter the traffic flow and affect the balance between the demand and capacity of the system—which in turn can threaten the stability of the system and the safety of the users. The green arrows also represent user inputs to the system such as flight plans or schedule changes that are part of the Collaborative Decision Making (CDM) process.

The Airspace users are at the bottom of the hierarchy and are mostly recipients of information and instructions. In special instances, when an airspace user experiences a significant event (emergency or fuel constraint) they can trigger feedback into the system. Under normal circumstances, however, airspace users are consumers of information and, for that reason, the arrow is shown in blue flowing from the communication channel.

This abstract model will be used to map the current ATC system flow and analyze the changes proposed for NextGen in the United States.

MAPPING THE CURRENT AIR TRAFFIC CONTROL FLOW

Air Traffic Control consists of multiple actors. ATCSCC is the nerve centre where centralized decisions are made. The ARTCCs, which control airspace for thousands of miles, plan for traffic for the sectors under each center's jurisdiction. The primary purpose of the ARTCC is to ensure the sector controllers' workloads are balanced. A Sector Controller monitors the traffic within a sector and hands over control to the adjacent sector. The Oceanic Controllers control the airspace across the ocean boundaries using procedure control and are often dependent on pilots' reports of time and location. When a flight enters the terminal area—the area closest to the airports, where traffic is usually heavy—the Sector/Oceanic Controller hands the control over to the Terminal Radar Approach Control (TRACON) who sequences the aircraft for arrival and then transfers control to the Tower. The Tower Control assigns runways and controls the traffic to the taxiway exits. The interaction between these control actors is best analyzed functionally by the role each plays in controlling the NAS—strategic planning, tactical planning, and tactical execution.

STRATEGIC PLANNING – Strategic planning is usually handled at the ATCSCC. As shown in Fig. 2, the strategic planning function works to maximize efficiency by developing predictions of capacity and demand more than one day in advance (even months in advance). Inputs include capacity and demand models based on airport use data, airspace for special use schedules (Military & BGA), airline flight schedules contained in the Official Airline Guide (OAG), infrastructure status (NAS), and historical flight-traffic-demand information (traffic trends). Another key component is historical weather information and past airport performance. ATCSCC also monitors the predictive capabilities of the model; assess the planned and executed strategies, and recommends changes [15].

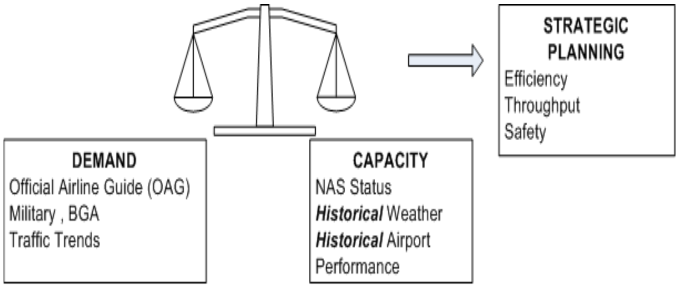

Fig. 2. Strategic Planning activity

TACTICAL PLANNING - Tactical planning involves ATCSCC and ARTCC, and happens on the day of the flight. The time window extends from 24 hrs to 1 hour before the flight. At this time, any changes to OAG data from airlines, filed flight plans for the day and the flights that are being tracked are taken as input to compute the demand side of the equation. On the capacity side, the current information on the NAS status, airport use and weather forecast are used. The output is a revised sector traffic plan.

The feedback occurs at this stage as the ARTCC tries to balance the workload of the sectors under its control. This feedback is triggered by the differences in the traffic forecasted during the strategic planning and the traffic anticipated on that particular day [16]. Even though the weather predictions are better because of the narrow time window, the predictions are not accurate in location (latitude, longitude and altitude), size (e.g. thunderstorms …) and timing. Feedback results in constraints imposed on the airspace users, which ultimately results in delays and cancellations.

TACTICAL EXECUTION - Tactical execution is best described by tracking the movement of a typical flight. The tactical execution phase begins at the airport, where the Tower Controllers regulate the ground traffic and manage the arrival and departure movements of aircraft. Fig. 3 depicts the information flow between the various entities during the tactical execution phase. The scheduled information flow is shown in blue and the feedback loops are shown in red.

Departure movement control – Even before the aircraft leaves the gate, the feedback loop for the destination airport can affect the departure performance. If the destination airport has significant delays due to weather, reduced capacity due to traffic, or equipment failures, they initiate restrictions, typically known as Airport Acceptance Rate (AAR), which is routed through the ATCSCC and translated into a Ground Stop (GS) or Ground Delay (GD) directive. A Ground Delay directive delays or halts the aircraft movement to all airports that feed the affected airport. These directives delay departures at the origin.

The Ground Controller at the tower clears the aircraft for departure, and the aircraft is pulled out of the gate and cleared for taxi. In some instances, the GS or AAR feedback information is received late, and some aircraft are delayed on the taxiway. This is the worst scenario for the airlines for two reasons. First, the subsequent departure delays are hard to predict and second, aircraft are burning fuel while delayed off the gate. Ground Stop or Ground Delay programs can cause flight cancellations and force the airlines to swap slots—that is, to fill a slot that opens up due to a cancellation with an alternative flight (which otherwise might be filled by a competitor). This is shown as the feedback loop from the airlines to the ATCSCC in Fig. 3.

When a departure delay occurs, the filed flight plan is not updated until after the aircraft is airborne, which alters the sector plan at the ARTCC. To cope with the change in the sector workload, sector delays are introduced, which affect departing aircraft and other airborne traffic in that sector. The departure movements can also be restricted due to weather, ground equipment status, or runway configuration change at the origin. All these delays cause airlines to miss their connecting schedules and add to the airline's fuel and labor cost. If there is no further delay, the aircraft is cleared for take-off from an assigned runway, and the tower control manages the traffic up to 5 miles from the airport. Control of the aircraft is then transferred to a TRACON or a Sector Controller.

When weather related events trigger local or national-level constraints, each of the players —ATCSCC, ARTCCs, sectors, airports and airlines—has a different view of the weather circumstance due to disparate sources of weather forecasts and the way the forecasts are integrated into each stakeholder's decision-making processes.

Sector Control Or En-Route Control – There are approximately 30 sector controls in each of 20 ARTCCs in the US. Once an aircraft is airborne, the Tower Controller hands over the control to the TRACON at major airports. At smaller airports, the control is transferred to a Sector Controller. On the departure side, the TRACON acts like a regular sector controller. The traffic volume in a particular sector is a function of the controller work load.

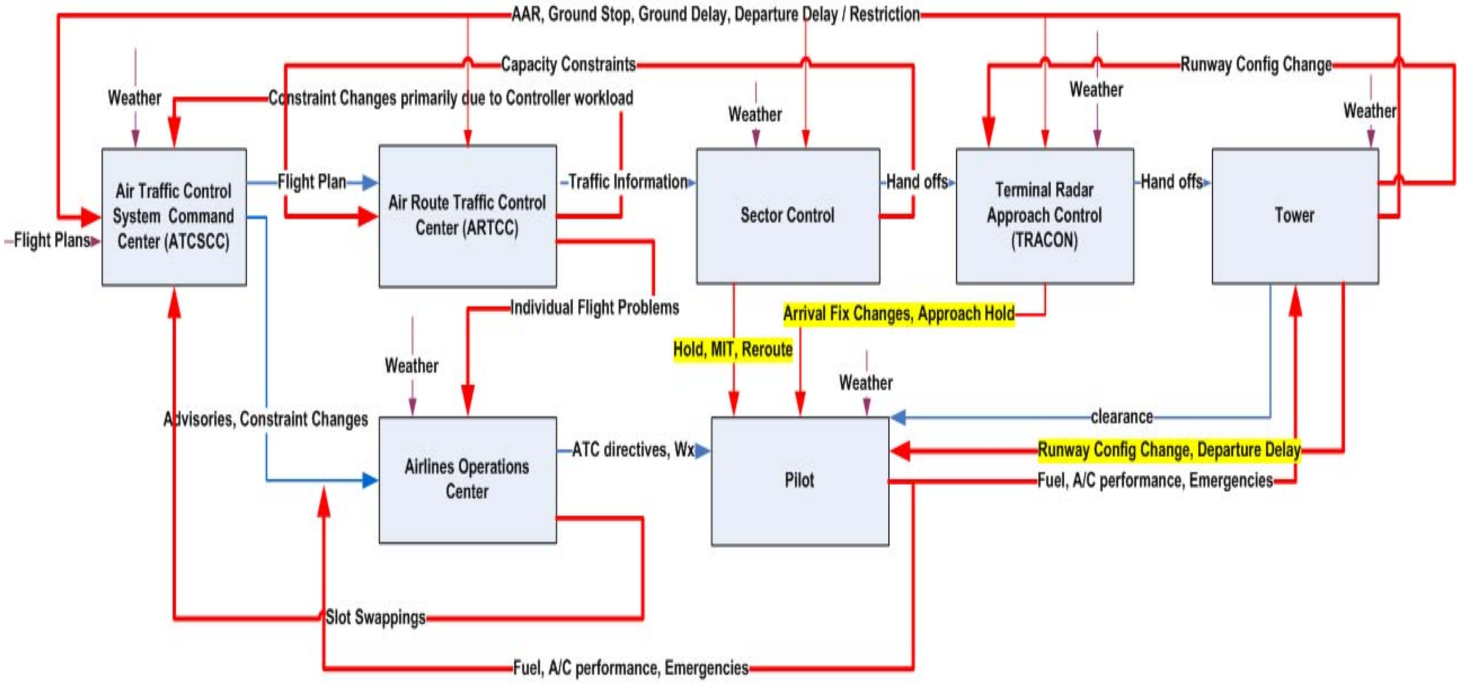

Fig. 3. Mapping of the current ATC flow

During normal operation, the Sector Controller ensures a safe separation between the aircraft and transfers control to the adjacent sector. Special circumstances such as adverse weather, radar equipment failure, or controller shortage can trigger an event that affects the traffic flow in a particular sector and adjacent sectors—or even trigger a NAS-wide constraint. Sector Controllers can initiate—often in one-way contact with the pilot—indefinite holds to stop the flow in their respective sector or until clearance is obtained from an adjacent sector. Sector Controllers also employ miles-in-trail (MIT), a constraint that specifies the minimum distance between aircraft to slow the traffic. A Sector Controller can re-route traffic through a different sector, too [17]. These re-routing and MIT procedures strain the workload in adjacent sectors, which manifest delays to other aircraft in the adjacent sectors. Without the intervention of the ATCSCC directing Ground Stop or Ground Delay constraints, this situation can escalate quickly and destabilize the system [18].

If any of these changes in sector control are not communicated in a timely fashion to the ARTCC or ATCSCC, the tactical and strategic planning activities are affected significantly. As well, an Airlines Operations Center (AOC) is unable to account for ground delays, en-route and MIT delays—highlighted as yellow in Fig. 3—which reduces the efficiency of both the airlines and the ATC system.

Oceanic Controllers are specialized Sector Controllers who manage the traffic that crosses the ocean. Since there is no surveillance radar coverage, the traffic control is manual and procedure based. The controllers rely on position and timing reports from pilots to track the traffic and impose safety margins for separation, as required.

Arrival Movement Control – The arrival phase begins when the en-route sector controller transfers control to the TRACON Arrival Controllers. Unlike departure control, arrival control reacts to the AAR and runway configuration constraints imposed by the airports. In response to a runway configuration change, the TRACON controller redirects a flight to the correct arrival fix, the location from which all aircraft begin their descent to the runway. Redirecting to a particular arrival fix can also occur to balance the load on the arrival fixes. To deal with an AAR, the TRACON introduces an approach hold. Approach holds are the leading cause of inefficiency for the airlines. The aircraft is on hold at a low altitude, where it operates very inefficiently.

Tower Control - The TRACON transfers control to the Tower Control when a landing slot becomes available. The Tower Control clears the aircraft for landing and guides the aircraft to the ground. Once the aircraft is on a taxiway, the Ground Controller takes charge of guiding the aircraft to the gate. Non-availability of gates can delay the aircraft on the tarmac and cause yet further unnecessary fuel burn.

Even though most communication between ATC and flight crews is one way, there are instances where a pilot can trigger feedback that affects the traffic flow. Pilot-triggered feedback includes emergencies, low fuel alerts, and aircraft performance problems.

DIFFERENCES IN PLANNING AND EXECUTION

An analysis of the deviations in execution from Strategic and Tactical planning produced the following list:

Weather Forecasting - Weather is a significant cause of delay in the NAS. Long term predictability continues to be the biggest challenge. Long-term forecasts are not assigned a probability, and thus the Strategic planning function must depend on historic weather data that does not predict near-term random events. Weather prediction for the tactical planning function is somewhat better, but still inaccurate in terms of location and timing [19]. This forces controllers to introduce larger time and space buffers around a weather pattern, which can significantly alter the traffic pattern. Another major source of error is the many sources of statistically unrelated weather forecasts and the subjective interpretations that affect decision making at the various control levels. The outcome is random feedback events that unnecessarily create delays and inefficient routes changes.

Individual Flight Characteristics - Modeling tools in the strategic and tactical planning phases do not take into account the specific performance of the aircraft types. When simulating traffic and delay scenarios, the Minimum Equipment List (MEL) and fuel carried by each airplane is not considered, and these shortcomings invalidate the planning and choke the system.

Communication Breakdown – Feedback loops are a form of communication between the various ATC actors, and timely communication is critical. Usually, the airlines are the last to receive revised planning, and thus the feedback loop is not closed when aircraft are re-routed or put on hold. The airlines are in the dark and often need to contact the ARTCC or the pilots themselves to inquire about individual flight situations to stay in the loop. Without timely information, the airlines are reacting to and disturbing an already destabilized control system.

FEEDBACK LOOP ANALYSIS

Feedback from random events is inevitable. However, these events can be minimized if planning processes are improved by means of better tools and more reliable forecast data. In general, feedback loops introduce inefficiency in the NAS; but some feedback is necessary to assure safety and performance. To be sure, no tool or computer aid can be perfect.

Ground Stop is better than the ground delay option—assuming a GS does not result in cancellation or revenue loss. Ground delays are better than MIT or re-routing options. MIT and re-routing increases fuel burn and labor cost. En-route delays are better than terminal area delays since the hold for a terminal area delay occurs at lower altitudes where the fuel burn is significantly greater.

GAP CLOSURE

The need for NextGen and SESAR is an outcome of the limitations in the traffic planning processes and the widening gap between the planning and execution functions. The inefficiency of the ATC system is hurting capacity growth and affecting the operations of all the airspace users. Haraldsdottir, et al [11], propose that planning activities at the ATCSCC aim to achieve airspace efficiency, that sector planning activities at ARTCC are designed to realize the desired throughput, and the tactical activities work towards safety. This author further recommends that any proposed change to the NAS structure is evaluated for efficiency, throughput, and safety. An appropriate balance between these performance figures of merit will stabilize the system and realize the required traffic capacity.

Of the three major causes of constraints in the system—that is, the feedback loops from adverse weather, infrastructure problems, and traffic volume—traffic is ranked third. The basic premise is that the purpose of NextGen, SESAR or any other ATC modernization is to accommodate the growing traffic.

MAPPING OF NEXTGEN IMPROVEMENTS

The proposed weather forecasting and Infrastructure changes will be analyzed to assess efficiency, throughput and safety, by mapping the revised processes to the abstract framework and measuring the effectiveness of the changes by means of feedback loops.

WEATHER - In the current system, weather is sourced independently at all levels, and the quality of the input varies. As well, the interpretation of the weather information differs amongst the various actors (airports, airlines, ATC), and the net result is unnecessary buffers added at all levels for separation assurance. The outcome is dramatically reduced traffic capacity.

NextGen aims to establish a single source of weather that is networked and made available to all users with a common interpretation easily understood by all. The weather forecasts will be four dimensional, with a time component added to the latitude, longitude and altitude. This net-centric view is represented in the abstract model by the bi-directional communication channel depicted in red in Figure 1.

By emphasizing uniform interpretation of common data [20], in addition to improving the accuracy and reliability of the forecasts, the output of the planning activities will be unified and better match reality. Improved en-route and terminal area weather predictions will enable ATC to negotiate re-adjusted flight schedules even before takeoff. This will promote better predictability all around and reduce the number of weather-related feedback loops in the system. This change alone will necessarily improve efficiency and increase capacity. On the safety front, the time dimension will enable planners to identify conflicts well before tactical operations. Better weather tools will enable crews to avoid bad weather all together, and thereby enhance passenger safety and comfort.

INFRASTRUCTURE IMPROVEMENTS - The perpetual delays and congestion in the current system are caused by the ground-based navigation aids. With the introduction of Automatic Dependent Surveillance–Broadcast (ADS-B), the NextGen plan intends to increase efficiency by allowing ADS-B-equipped aircraft to fly direct routes—great circles instead of the jet routes. The improved surveillance capability will provide better situational awareness in the cockpit, and thereby increase safety [21]. ADS-B can also be used to manage surface movement. This capability will also improve the safety and efficiency of the system. Arguably, the reduced separation between aircraft enabled by ADS-B will be the most important benefit.

The ADS-B functionality is represented in the abstract model by the bi-directional communication channel shown in Figure 1. This communication transports the situational awareness information to both the flight crews and the controllers.

The surveillance capability of ADS-B is expected to reduce MIT and en-route hold procedures. The effect will be reduced controller workload, which is the primary cause of capacity constraints in the system today.

SUMMARY AND FUTURE WORK

This paper analyzes the efficiency of the current air transportation system and the negative impact it has on the economy. With the predicted growth in air traffic, the situation will likely worsen and have a huge impact on the economy, the environment, and safety. This circumstance has motivated the NextGen and SESAR initiatives in the United States and Europe. The revised policies and new technologies proposed by these programs further motivate the need for a framework to analyze and validate the effect of these changes and promote a uniform system in the US and Europe.

This paper presents an abstract model to achieve these objectives. In the model, the information flows forward to represent the planning processes in the hierarchical organization. Feedback events represent pseudo-random events that the forward information flow cannot account for. This communication topology is necessary to represent the unaccounted for (and thus random) events that can originate at any level and affect any level of hierarchy. That is, the model represents the "external stimuli" (such as adverse weather) that can disrupt the stability of the system. The model also accommodates net-centric improvements that more effectively interconnect the ATC components. The bi-directional communication channel simulates the network information flow. In order to validate the abstract model, the current ATC system is mapped to the model, with feedback loops to reproduce the spurious events that originate at any level. The tactical deviations from the planning function are highlighted, and the corresponding impact on the system is described. The various feedback loops are analyzed to identify the impact on the system stability. This initial analysis is qualitative. The model will be extended to enable quantitative analyses in the future.

Infrastructure improvements proposed by NextGen and SESAR are mapped to the bi-directional communication channel to represent communication improvements such as ADS-B and Controller-Pilot Data Link Communication (CPDLC). These technologies enable more efficient sharing of information between flight crews and controllers.

There is a growing concern for equipment compatibility among the airspace stakeholders. While SESAR and NextGen both state common goals to increase capacity and improve safety and efficiency, the philosophies for achieving these goals are very different. For example, the US policy focuses on weather enroute, while the Europe initiative concentrates on low-visibility at airports [22]. Similarly, the usefulness of ADS-B is perceived differently in the US and Europe. The NextGen plan depends on ADS-B, while Europe considers it useful for low-density airspace applications (even though traffic density in Europe is greater than the US). Additionally, the US mandate for ADS-B is 2020. In Europe, the goal is 2015.

Nevertheless, the abstract model is sufficiently general to represent both systems. The next step is to extend the model and quantify the relative benefits of the weather and equipment-related improvements proposed by each initiative.

By modeling the ATC system hierarchically with different levels of abstraction, the interplay between systems and policies can be evaluated. Accordingly, this framework fosters the work to identify the best-value approach, and thereby promote uniform practices, procedures, and airplane equipage globally.

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